



ORIGINAL ARTICLE

The relationship between lower limb proprioception and balance performance in children with cerebral palsy: a multisystem and multi-joint approach

Nina JACOBS ¹*, Evi VERBECQUE ¹, Kaat DESLOOVERE ^{2, 3},
Els ORTIBUS ^{4, 5}, Ann HALLEMANS ⁶, Pieter MEYNS ¹

¹Rehabilitation Research Centre (REVAL), Department of Rehabilitation Sciences, Hasselt University, Diepenbeek, Belgium; ²Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium; ³Clinical Motion Analysis Laboratory, University Hospital of Leuven, Pellenberg, Belgium; ⁴Research Group for Neurorehabilitation, Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium; ⁵Center for Developmental Disabilities, Leuven, Belgium; ⁶Research Group MOVANT, Department of Rehabilitation Sciences and Physiotherapy (REVAKI), University of Antwerp, Wilrijk, Belgium

*Corresponding author: Nina Jacobs, Rehabilitation Research Centre (REVAL), Department of Rehabilitation Sciences, Hasselt University, Wetenschapspark 7, 3590 Diepenbeek, Belgium. E-mail: nina.jacobs@uhasselt.be

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ABSTRACT

BACKGROUND: Balance problems are a frequent focus of rehabilitation approaches in children with cerebral palsy (CP). Although proprioceptive impairments, affecting 46–90% of children with CP, are commonly observed, their role in postural control remains insufficiently understood. **AIM:** Given the multisystemic nature of postural control, this study aimed to investigate the association between lower-limb proprioception (hip, knee, ankle) and distinct postural control systems in children with CP compared to typically development (TD).

DESIGN: Cross-sectional case-control study.

SETTING: Different outpatient settings and the community.

POPULATION: Children aged 5-12 years with TD (N.=30, 8.6±2.2y; boys: 15) and spastic CP (N.=32, 8.4±2.1y; boys: 16; GMFCS-I/II/III: 24/7/1; uni-/bilateral: 17/15).

METHODS: Postural control was assessed using the age-specific Kids-Balance Evaluation Systems Test – extended version (Kids-BESTest-2). Hip, knee, and ankle proprioception were assessed using passive-ipsilateral Joint-Position-Reproduction (JPR). Joint Reproduction Error (JRE, °) was calculated from 3D kinematics for the joints of the dominant (JREd) and nondominant (JREnd) leg. Associations between Kids-BESTest-2 (total and domain scores, %) and summed joint JRE_{ankle}, JRE_{knee} and JRE_{hip} (JREd+JREnd) were analyzed using general linear models with correction for multiple testing.

RESULTS: JRE_{total} was not significantly associated with Kids-BESTest-2 scores in either group (P>0.01). In CP, higher JRE_{hip} (reflecting poorer proprioception) was significantly associated with lower total ($\eta_p^2=0.24$, P<0.001) and 3 of 5 domain scores ($\eta_p^2=0.14-0.22$, P<0.004), reflecting poorer balance performance. Similarly, JRE_{knee} predicted scores for ‘Transitions and Anticipatory Postural Adjustments’ ($\eta_p^2=0.13$, P=0.008). Across both groups, poorer hip (JRE_{hip}) and ankle (JRE_{ankle}) proprioception were significantly associated with poorer performance for ‘Transitions and Anticipatory Postural Adjustments’ ($\eta_p^2=0.16$, P=0.003) and ‘Reactive postural responses’ ($\eta_p^2=0.12$, P=0.005), respectively.

CONCLUSIONS: Postural control deficits in children with CP affect multiple systems, and each system is associated with joint-specific proprioceptive impairments (particularly at the hip), rather than overall proprioceptive accuracy. These findings suggest task-dependent and pathology-dependent associations, the latter likely reflecting limitations in compensatory proprioceptive reweighting across lower-limb joints. **CLINICAL REHABILITATION IMPACT:** These findings underscore the need for a system- and joint-specific approach to better understand postural control deficits in children with CP and tailor interventions that enhance proprioceptive input during task-specific balance training.

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KEY WORDS: Postural balance; Proprioception; Lower extremity; Cerebral palsy.

Cerebral palsy (CP) is the most common motor disability in children, affecting approximately 1.6 to 3 per 1,000 live births.¹ It is caused by a non-progressive lesion in the developing fetal or infant brain, leading to movement and posture disorders that can impact all domains of the International Classification of Functioning, Disability, and Health (ICF).² Postural control deficits are a key feature of CP, typically manifesting early in childhood and hindering motor development, delaying a child's ability to perform functional activities such as standing and walking.³ Although 83% of children with CP achieve independent standing and walking by preschool age (GMFCS I-III),⁴ postural control deficits remain a major challenge, even in higher-functioning individuals.⁵⁻⁷ These deficits contribute to impaired mobility,³ increased fall risk,⁸ and are among the most common concerns in rehabilitation practice.⁹ However, despite the increasing recognition of postural control deficits in CP over the past decades, the underlying causes remain insufficiently understood.

Postural control, defined as the ability to control the center of mass (COM) in relation to the base of support,¹⁰ is considered a complex motor ability that relies on sensorimotor integration.¹¹ Specifically, to know when and how to generate postural muscle synergies, the central nervous system (CNS) must have an accurate perception of where the body is located in space and how different body segments are positioned relative to each other. This internal schema is built upon proprioceptive signals that underlie body awareness.¹² Such real-time proprioceptive information enables the CNS to make postural adjustments, either proactively (to prepare for predicted, self-initiated disturbances, such as walking), or reactively (to respond to unexpected, external disturbances, such as slipping while walking).¹¹ Depending on the specific task and environment (*e.g.*, sensory context), a child relies on different types of (sensory input for) postural adjustments to ensure control of the COM. This illustrates that postural control is not a general skill, but rather a task-specific ability, dependent on the dynamic interaction of multiple underlying systems, as defined by Horak.¹³

However, in CP, a lesion in the developing brain can disrupt this sensorimotor interaction, leading to deficits in postural control that can affect multiple systems.⁷ As a result, children with CP exhibit abnormal postural muscle synergies, such as agonist-antagonist co-contraction and slower or insufficient muscle responses during various tasks.^{14, 15} While this may initially seem attributable to motor impairments such as spasticity or muscle weakness, these symptoms only partially explain the observed

postural control deficits.^{16, 17} Proprioception likely plays a significant role as well, given that delayed and co-contracted muscle responses are commonly associated with reduced proprioceptive feedback.¹¹ Moreover, children with CP show difficulties adapting their postural muscle synergies to changes in the degree of self-initiated (*e.g.*, lifting heavier loads)¹⁸ or external postural disturbances (*e.g.*, larger or faster platform perturbations),¹⁹ further suggesting a link between diminished proprioceptive feedback and impaired postural control. Notably, CP is not a purely motor-related disorder, and proprioceptive deficits are also apparent in 46% to 90% of children with CP, affecting both upper²⁰ and lower limb joints.²¹ However, whereas the link between upper limb proprioception and manual function in CP is well established,²² the contribution of these lower limb proprioception deficits to postural control, particularly in relation to its different underlying systems, remains less understood.

To date, only a limited number of studies have explored the relationship between lower limb proprioception and postural control in CP. A case-control study found that children with CP who exhibited poorer hip proprioception walked at slower speeds.²³ While these children also experienced greater difficulty in maintaining their balance in sensory-challenging environments (*e.g.*, standing with eyes closed), the direct association with poorer hip proprioception was observed only across the study population. More recent preliminary evidence suggests a similar pattern for ankle proprioception; while an association with postural sway in comparable tasks was reported,²⁴ this was likewise derived from a combined analysis of children with CP and typically developing (TD) peers, limiting the interpretability of these findings. In contrast, the importance of ankle proprioception appears more clearly established in reactive postural control, given that children with CP with poorer ankle proprioception exhibit greater difficulty in eliciting appropriate postural responses to external perturbations of varying magnitude and direction.²⁵ Besides this, children with CP also face challenges during self-initiated movements (*e.g.*, forward reaching), particularly in generating sufficient postural adjustments prior to the movement¹⁸ and in reaching their limits of stability while moving.²⁶ However, the role of lower limb proprioception with respect to deficits in these postural control systems remains unexplored. Given not only the scarcity of studies on this topic but also their narrow focus, targeting only one or two postural control systems with limited variation in tasks, it remains unclear whether lower-limb proprioception acts as a general determinant of postural control, across any task

within the multisystem framework defined by Horak,¹³ or whether its relationship is task-specific. On top of that, knee proprioception may also be affected in children with CP.²⁷ Considering its suggested role in postural control in children with other neurodevelopmental disorders, such as Developmental Coordination Disorder,²⁸ it is reasonable to hypothesize that knee proprioception, along with ankle and hip proprioception, may contribute to the observed postural control deficits in children with CP. However, these joint-specific contributions, with respect to the different underlying postural control systems, have yet to be investigated.

Therefore, the aim of this study is to investigate the association between the previously identified task-specific deficits in postural control and lower limb proprioception in children with CP. Using a multisystem and -joint approach, this study will (1) evaluate the extent to which lower limb proprioception, in general (across all joints), is associated with the different systems underlying postural control and (2) explore the extent to which proprioception of various lower limb joints (ankle, knee, hip separately) is involved differently in children with CP and age- and gender-matched TD children.

Materials and methods

This case-control study was conducted between April 2022 and December 2024 and approved by the Committee for Medical Ethics (CME) of Antwerp University Hospital/UZA, Hasselt University and UZ Leuven/KU Leuven on February 18, 2022 (ID: B3002021000145, chairperson: Prof. P. Michielsen). Written informed consent was obtained from the children's parents before participation. Additionally, verbal informed assent was obtained from the children after explaining the test procedures.

Participants

Children were recruited through regular and specialized elementary schools, private practices, Cerebral Palsy Reference Centers from the UZA and UZ Leuven, as well as through acquaintances and social media.

Children with CP were included if they met the following inclusion criteria: aged 5 years and 0 months to 12 years and 11 months, diagnosed with either unilateral or bilateral spastic CP based on clinical symptomatology, and classified as ambulatory (GMFCS I-III). The control group consisted of TD children, individually matched for age and group-matched for sex at birth, all born at term and without any neuromotor or neurodevelopmental disorders. Comorbidities, *i.e.*, autism spectrum disorder and

attention-deficit/hyperactivity disorder, were allowed in both groups to ensure a representative sample. Detailed information on full inclusion and exclusion criteria, including restrictions on recent medical treatments, psychosocial well-being (as assessed by the Dutch Strengths and Difficulties Questionnaire, SDQ) and other conditions (*e.g.*, cognitive disabilities, screened via clinical referral, parental questionnaire and task familiarization by the examiner) that could interfere with test performance, can be found in our previous study.²¹

Data collection and analyses

The Balance Evaluation Systems Test for children – extended version (Kids-BESTest-2)

Balance performance was assessed using an extended version of the original full Kids-BESTest.^{29, 30} The Kids-BESTest is a comprehensive criterion-referenced test designed to identify and classify postural control deficits across six different domains (28 to 36 items depending on the age category): 1) “biomechanical constraints”; 2) “limits of stability and verticality”; 3) “transitions and anticipatory postural adjustments”; 4) “reactive postural responses”; 5) “sensory orientation”; and 6) “stability in gait”; thereby aligning with the multisystemic nature of postural control.¹³ Each item is scored from zero (worst performance) to three (best performance) on a four-point ordinal scale, using age- and task-specific scoring criteria that consider both quantitative and qualitative performance.⁷ Domain scores are calculated by summing item scores and expressing them as a percentage of the maximum score for that respective domain. The total Kids-BESTest-2 score is the average of these percentage scores across all six domains. The original Kids-BESTest has demonstrated good intra-rater, inter-rater, and test-retest reliability in TD and CP children aged 8 to 14 years.^{29, 30} Concurrent validity has been investigated for individual items, such as the Forward Reach Test, Lateral Reach Test, and the (Modified) Clinical Test of Sensory Interaction in Balance.^{31, 32} The Kids-BESTest-2 is sensitive in differentiating balance performance between children with CP and TD peers.⁷

Joint position reproduction protocol

Joint Position Sense was assessed using the passive-ipsilateral Joint Position Reproduction (JPR) protocol, as described previously.^{21, 33} Briefly, the procedure followed an experience-memory-reproduction sequence. The examiner passively moved the blindfolded child's limb to a predefined target position (experience), held it for 5 seconds

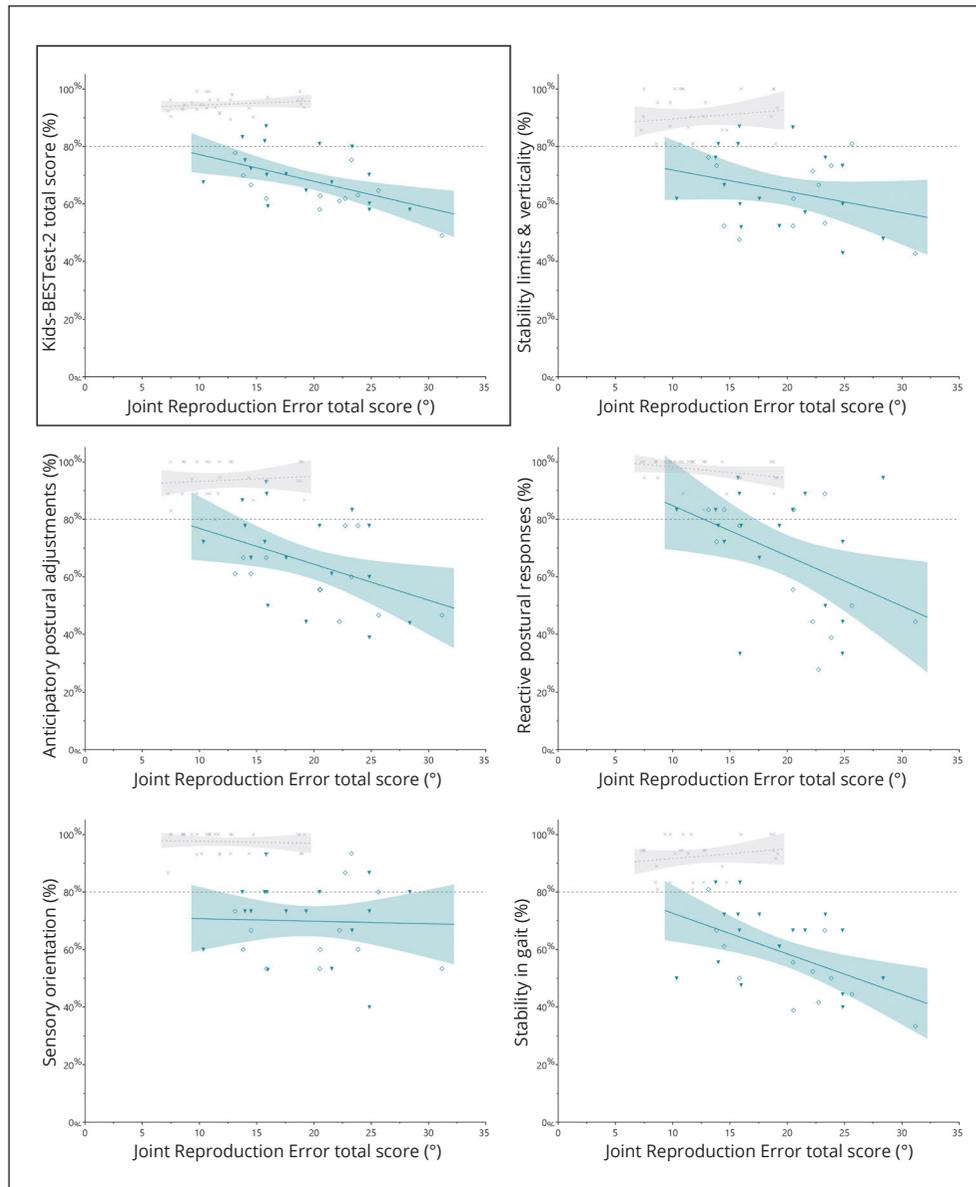


Figure 1.—Association between balance performance and total lower limb proprioception (JRE_{total}). Scatterplots of Kids-BESTest-2 total and domain (%) scores by absolute Joint Reproduction Error (JRE) values ($^{\circ}$) for spastic unilateral CP (\blacktriangledown , $N=17$), bilateral CP (\diamond , $N=12$) and TD children (\times , $N=29$) aged 5 to 12 years. The JRE_{total} (data point) represents the sum of JRE across all joints (hip, knee, ankle) for dominant and non-dominant sides. Higher values correspond to poorer proprioception. Depending on age category, 28 to 36 Kids-BESTest-2 items were summed to produce a total score and 5 domain scores (%). A score of $< 80\%$ cut off (---) indicates postural control deficits, with lower percentages reflecting poorer balance performance. Separate regression lines are shown for each group (CP=— ; TD=- -) with the shaded band representing the 95% confidence interval in CP (blue) and TD group (grey).

to allow memorization (memory), and returned it to the start position. Subsequently, the same limb was passively moved again in the same range and the child pressed a stop button to re-identify the memorized position (reproduction). Detailed illustrations of this setup are provided in Figure 1 of our previous study.³³ Target positions were defined in the sagittal plane (hip: 20° flexion, knee: 30° extension and ankle: 30° dorsiflexion), relative to the standardized sitting start position (hip: 70° flexion, knee: 90° flexion and ankle: maximum plantar flexion), using an inclinometer (Dr. Rippstein, Lutry, Switzerland) dis-

tally attached to the moving segment. Hip, knee and ankle JPR were repeated three times for both the dominant and non-dominant leg, in a randomized order and at the same movement speed (5° per second). In total, each child performed 18 trials ($3 \text{ trials} \times 3 \text{ joints} \times 2 \text{ legs}$). The dominant leg was defined as the one the child was most comfortable standing on while kicking a ball (representing the limb preferred to perform the balancing aspect of the task).

The absolute joint reproduction error ($JRE,^{\circ}$), representing the difference between the target and reproduction angle, was calculated using 3D kinematics from optoelec-

tronic motion capture (VICON, Oxford Metrics, UK) comprising 10 high-speed (100Hz) infrared cameras. Twenty-six reflective markers were placed according to ISB lower limb recommendations.³⁴ Joint angles were derived using Vicon Nexus software (v2.12.1; Vicon Inc.), and JRE calculations were performed in MATLAB R2022a. For a more detailed description of the applied JPR procedure and instrumentation, we refer to our previous study.²¹

Hip, knee and ankle JPR was expressed as the best error (*i.e.*, smallest JRE across three trials), as this approach improves reliability and precision in children.³⁵ In both TD and CP children (for bilaterally affected joints), JPR performance on dominant side was comparable to that on the nondominant side.²¹ In line with these findings, the following JRE variables were defined by summing these best error values:

- 1) Joint-specific JRE: calculated as the sum of the best JRE of the dominant and non-dominant side for each joint separately, resulting in a best JRE_{ankle} (best $JRE_{d_{ankle}}$ + best $JRE_{nd_{ankle}}$), JRE_{knee} (best $JRE_{d_{knee}}$ + best $JRE_{nd_{knee}}$), and JRE_{hip} (best $JRE_{d_{hip}}$ + best $JRE_{nd_{hip}}$);

- 2) Total JRE: calculated by adding the summed best JRE of the ankle, knee and hip, resulting in a best JRE_{total} (best JRE_{ankle} + best JRE_{knee} + best JRE_{hip}). This summative approach across sides and joints was chosen over averaging, as it provides a more sensitive measure that better reflects the cumulative extent of proprioceptive errors across the lower limbs, whereas averaging can mask meaningful changes in distribution.

Sample size calculations

Based on an effect size estimated from the correlation coefficient between hip proprioception (JRE , °) and postural sway in standing (COM displacement, mm) reported in a comparable population,²³ a minimum sample of 55 children in total (approximately 28 per group) was needed to detect a correlation equivalent to or larger than $|r|=0.44$, assuming a power of 80% and an alpha level of 0.01. Power analyses for ankle proprioception (JRE , °) in relation to reactive postural control (BESTest, %) in CP²⁵ indicated that this sample size ($N=28$) was also sufficiently large to achieve 80% power, as a strong correlation ($r=0.70$) could be detected with as few as 19 children in the CP group. The power analysis was conducted in G*Power version 3.1.9.7 using the bivariate correlation model.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics (version 29.0.1) for Windows.

To characterize the population, descriptive statistics were calculated for demographic, anthropometric and psychosocial factors (SDQ), as well as for CP-specific classification measures of gross motor function, topography and lesion type (Table I). Descriptive data for JRE variables are presented in Table II. Group differences were assessed using two-tailed independent samples *t*-tests or Mann-Whitney U tests for non-normally distributed data. Categorical variables were analyzed using a Chi-squared test or Fisher's Exact Test when more than 20% of expected counts were <5.

To investigate whether lower limb proprioception in general, as measured by JRE_{total} , predicts variance in Kids-BESTest-2 total and domain scores (%) and whether this association differs between groups (first aim), a General Linear Model (GLM) was performed. In this analysis, group (CP vs. TD) was treated as a fixed factor, JRE_{total} (in °) was included as a covariate, and both main effects and the interaction effect (Group \times JRE_{total}) were initially considered. To examine joint-specific contributions to balance performance (second aim), an additional GLM was performed, in which JRE_{hip} , JRE_{knee} , and JRE_{ankle} were included as separate covariates, each interacting with group (Group \times JRE_{hip} , Group \times JRE_{knee} , Group \times JRE_{ankle}). As all Variance Inflation Factors values remained below 5,³⁶ no evidence of problematic multicollinearity was found, and all JRE covariates were retained in the model. Age was not considered a confounding factor and therefore not included as a covariate, as 1) Kids-BESTest-2 scores were already corrected for age using age-specific checklists and scoring criteria; and 2) partial correlations between age and the predictor JRE variables were weak to moderate ($r=-0.22$ at most), with $|r|$ below the 0.7 threshold³⁶ (Supplementary Digital Material 1: Supplementary Table I). Model simplification was applied in both GLM analyses by stepwise removal of non-significant interaction terms and main effects ($P>0.01$). Given the strong correlations observed between the total and domain scores (Supplementary Digital Material 2: Supplementary Table II), a Bonferroni correction for multiple testing was applied to adjust the significance levels in the GLM and control for potential Type I errors ($\alpha=0.05/5$, reflecting 6 GLMs minus 1 to account for the initial omnibus test). Outliers, identified by standardized residuals greater than $|3|$, were excluded from the final model to ensure robustness of the results. In case of missing data, a maximum likelihood model fit was used, which yields valid results under the Missing At Random assumption for the missingness. All assumptions were assessed prior to the GLM analysis and

TABLE I.—Population characteristics.

	CP (N.=29)		TD (N.=29)		P value
	Mean (SD) or Median (IQR)	/min-max	Mean (SD) or Median (IQR)	/min-max	
Age, years	8.5 (2.4)	/5.1-12.8	8.6 (2.0)	/5.2-12.7	0.379 ^a
Height, cm	130.8 (14.6)	/104.0-153.6	132.6 (12.2)	/113.0-161.7	0.674 ^a
Leg length dominant leg, cm	69.6 (10.5)	/51.0-97.0	70.8 (8.1)	/57.4-88.5	0.631 ^a
Leg length nondominant leg, cm	69.2 (10.5)	/50.2-97.4	70.7 (8.0)	/57.5-88.5	0.546 ^a
BMI, kg/m ²	16.5 (2.2)	/13.3-21.4	18.6 (3.8)	/14.1-26.4	0.125 ^b
Boys:girls (N)	14:15		14:15		0.612 ^c
SDQ total problem score	9.7 (5.3)	/3-20	7.1 (5.1)	/2-16	0.255 ^a
Emotional problems [§]	2.0 (3.5)	/0-6	2.0 (3.8)	/0-6	1.000 ^b
Conduct problems [§]	1.0 (2.5)	/0-5	0.0 (2.5)	/0-5	0.324 ^b
Hyperactivity [§]	3.0 (4.0)	/0-9	3.0 (4.5)	/0-6	0.582 ^b
Peer problems [§]	2.0 (3.0)	/0-4	0.0 (1.0)	/0-3	0.057 ^b
Prosocial behavior	8.0 (3.0)	/3-10	9.5 (1.0)	/6-10	0.200 ^b
Impact: no impact (N)	19:10		12:17		0.168 ^c
Impact score	1.5 (3.0)	/0-4	1.0 (1.8)	/0-2	0.734 ^b
Unilateral: bilateral (N.)	17:12				
GMFCS level I:II (N.)	22:7				
MRICS (N.)					
Maldevelopments	2 (7%)				
Predominant white matter injury	20 (69%)				
Predominant grey matter injury	5 (17%)				
Miscellaneous	2 (7%)				

[§]Item that is considered in the total problem score of the SDQ; ^aresult of an independent samples *t*-test with data presented as mean (SD); ^bresult of a Mann-Whitney U-Test with data presented as median (IQR); ^cresults of a Chi-squared test with data presented as frequency (%).

TABLE II.—Descriptive statistics for lower limb proprioception.

	CP (N.=29)		TD (N.=29)		P value
	Mean (SD) or Median (IQR)	/min-max	Mean (SD) or Median (IQR)	/min-max	
Joint position reproduction (JPR)					
JRE _{total} (°)	19.6 (5.4)	/10.3-31.2	12.6 (3.7)	/7.2-19.1	<0.001 ^a
JRE _{hip} (°)	4.7 (2.2)	/1.2-10.1	3.1 (1.8)	/0.7-6.4	0.005 ^a
JRE _{knee} (°)	6.2 (4.6)	/1.7-15.9	4.4 (3.6)	/0.6-10.5	0.017 ^b
JRE _{ankle} (°)	8.1 (3.2)	/2.8-14.4	4.7 (2.5)	/1.4-10.4	<0.001 ^a

^aResult of an independent samples *t*-test with data presented as mean (SD); ^bresult of a Mann-Whitney U-Test with data presented as median (IQR).

were found to be met. Normality of residuals was evaluated through visual inspection (Normal QQ-plot and histogram) and the Shapiro-Wilk test, and no violations of linearity or homoscedasticity were identified from residual plots. Effect sizes for group and JRE effects were calculated using partial eta squared: $\eta^2_p = SS_{effect} / (SS_{effect} + SS_{error})$, in which SS_{effect} reflects the sum of squares of the group or JRE effect and SS_{error} represents the sum of squares for the residual error. The partial eta squared (η^2_p) represents the proportion of variance in Kids-BESTest-2 scores explained by group or JRE, while controlling for the other predictor, and was interpreted as small (0.01-0.059), medium (0.06-0.13) or large (≥ 0.14) based on Cohen's guidelines.³⁷ The biomechanical constraints (domain 1) were considered outside the scope of the analyses for the second

aim and therefore not included as a response variable, as they evaluate the musculoskeletal requisites a child needs to perform postural control tasks.

Results

Participants

From a total of 80 eligible participants, 62 agreed to participate and were included: 32 children with CP (8.5±1.7 years; 53% unilateral; 66% GMFCS-I) and 30 age-matched TD children (8.7±1.6 years), with an equal sex at birth distribution across both groups. Demographic, anthropometric and psychosocial (SDQ) characteristics did not differ between the groups and are detailed in Table I.

Further details on the recruitment and selection process are provided in Supplementary Digital Material 3, Supplementary Table III.

Missing data (2.42%) were primarily due to technical issues (e.g., marker visibility), resulting in 21 missing trials for hip (15) and knee JPR task (6) out of 1110 completed trials. One 7-year-old CP child refused to complete the hip JPR task (6) due to discomfort with the markers. As a result, the best JRE_{hip} , JRE_{knee} and JRE_{ankle} could be obtained for 59, 59, and 62 children, respectively, enabling a reliable JRE_{total} calculation for 58 children in the final analysis (Table I, II, III). One of these CP children (11 years old) also could not perform the lateral compensatory stepping tasks (2 items) in domain 4, which were not considered in his total Kids-BESTest-2 score. Descriptive data of the Kids-BESTest-2 and proprioception measures for the full sample (N.=62) are provided in Supplementary Digital Material 4, Supplementary Table IV.

When reproducing joint positions, JRE_{total} was significantly larger in children with CP ($19.6 \pm 5.4^\circ$) compared to TD children ($12.5 \pm 3.7^\circ$, $t=5.9$, $P<0.001$). This was determined by significant increases in JRE_{ankle} ($t=4.7$, $P<0.001$), JRE_{hip} ($t=2.9$, $P=0.005$), and to a smaller extent, JRE_{knee} ($t=2.6$, $P=0.012$), with values increasing by 41% to 72% compared to TD children (Table II).

When performing the Kids-BESTest-2, CP children scored significantly worse than TD children across all balance domains, as reflected by significant main effects of

group (domain: $F_{(1, 55)}=20.1 - 70.4$, $\eta_p^2=0.27 - 0.56$; total: $F_{(1, 55)}=115.2$, $\eta_p^2=0.68$, $P<0.001$, Table III).

Association between balance performance and total lower limb proprioception

No significant interaction effect for $Group \times JRE_{total}$ was found for the total or any of the domain scores, nor was there a main effect of JRE_{total} observed ($P>0.01$, Table III and Figure 1).

Association between balance performance and joint-specific lower limb proprioception

A significant interaction effect $Group \times JRE_{hip}$ indicated that higher JRE_{hip} values were significantly associated with poorer total Kids-BESTest-2 scores ($F_{(1, 54)}=17.6$, $P<0.001$), ‘Stability Limits and Verticality’ ($F_{(1,54)}=15.2$, $P<0.001$), ‘Sensory orientation’ ($F_{(1,54)}=10.1$, $P=0.002$) and ‘Stability in gait’ ($F_{(1,54)}=9.1$, $P=0.004$) in children with CP, but not in TD children. Similarly, JRE_{hip} and JRE_{knee} predicted children’s ‘Transitions and Anticipatory Postural Adjustments’ domain scores, with JRE_{hip} being a significant predictor across both groups ($F_{(1,53)}=9.8$, $P=0.003$), whereas JRE_{knee} predicted domain scores only in children with CP ($F_{(1,53)}=7.7$, $P=0.008$). Additionally, JRE_{ankle} , in either CP or TD children, was significantly associated with domain scores for ‘Reactive Postural Responses’ ($F_{(1,55)}=8.4$, $P=0.005$). For all the above findings, the association was moderate to large in effect size

TABLE III.—General Linear Model results for group differences in Kids-BESTest-2 scores considering JRE_{total} .

	Score, % (mean±SD)		Effect	F	P	η^2p
	CP (N.=29)	TD (N.=29)				
Total	68.3±9.1	94.7±2.8	Group	115.16	<0.001*	0.68
			JRE_{total}	4.05	0.049	0.07
			$Group \times JRE_{total}$ §	5.34	0.025	0.09
Stability limits and verticality	64.7±13.3	90.2±7.6	Group	43.51	<0.001*	0.44
			JRE_{total}	0.06	0.807	0.00
			$Group \times JRE_{total}$ §	3.09	0.084	0.05
Anticipatory postural adjustments	64.9±14.9	93.5±6.5	Group	41.16	<0.001*	0.43
			JRE_{total}	2.16	0.147	0.04
			$Group \times JRE_{total}$ §	2.70	0.106	0.05
Reactive postural responses	68.0±20.6	97.3±4.6	Group	20.10	<0.001*	0.27
			JRE_{total}	6.82	0.012	0.11
			$Group \times JRE_{total}$ §	2.69	0.107	0.05
Sensory orientation	69.8±13.4	97.4±3.8	Group	70.41	<0.001*	0.56
			JRE_{total}	0.01	0.906	0.00
			$Group \times JRE_{total}$ §	0.02	0.898	0.00
Stability in gait	59.1±13.9	92.3±6.4	Group	66.82	<0.001*	0.55
			JRE_{total}	4.99	0.030	0.08
			$Group \times JRE_{total}$ §	6.45	0.014	0.11

JRE; joint reproduction error; F: F-statistic obtained from final General Linear Model; η^2p : partial eta squared, with 0.01-0.059=small; 0.06-0.13=medium and ≥ 0.14 =large effect.

*P values indicating statistical significance ($P<0.01$), after §non-significant interaction terms and main effects were stepwise **, ***, ****, ***** removed from final model.

($\eta_p^2=0.12-0.24$) and negative, indicating that the higher the JRE value, reflecting poorer proprioception, the lower children’s Kids-BESTest-2 total and domain scores (Table IV, Figure 2).

Discussion

This study provides novel evidence that postural control in children with CP is not only impaired across multiple un-

derlying systems, but also associated with proprioceptive impairments at multiple lower limb joints, highlighting the importance of a joint- and system-specific approach to understanding postural control deficits in this population. Specifically, our findings suggest that the joint affected by proprioceptive dysfunction (primarily the hip), rather than the overall severity of proprioceptive deficits, plays a significant role in determining whether a child with CP

TABLE IV.—General Linear Model results for group differences in Kids-BESTest-2 considering JRE_{ankle} , JRE_{knee} and JRE_{hip} .

	Score, % (mean±SD)		Effect	F	P	η^2p
	CP (N.=29)	TD (N.=29)				
Total	68.3±9.1	94.7±2.8	Group	11.35	0.001*	0.17
			JRE_{hip}	9.85	0.003*	0.15
			$JRE_{knee} §,*****$	2.33	0.133	0.04
			$JRE_{ankle} §,****$	0.03	0.856	0.00
			Group* JRE_{hip}	17.57	<0.001*	0.24
			Group* $JRE_{knee} §,***$	3.64	0.062	0.07
Stability limits and verticality	64.7±13.3	90.2±7.6	Group* $JRE_{ankle} §,**$	0.01	0.998	0.00
			Group	0.84	0.363	0.02
			JRE_{hip}	7.76	0.007*	0.12
			$JRE_{knee} §,****$	0.00	0.986	0.00
			$JRE_{ankle} §,*****$	4.00	0.051	0.07
			Group* JRE_{hip}	15.17	<0.001*	0.22
Anticipatory postural adjustments	64.9±14.9	93.5±6.5	Group* $JRE_{knee} §,****$	3.79	0.057	0.07
			Group* $JRE_{ankle} §,***$	0.58	0.451	0.01
			Group	3.66	0.061	0.07
			JRE_{hip}	9.76	0.003*	0.16
			JRE_{knee}	8.05	0.006*	0.13
			$JRE_{ankle} §,****$	4.99	0.030	0.09
Reactive postural responses	68.0±20.6	97.3±4.6	Group* $JRE_{hip} §,***$	1.48	0.230	0.03
			Group* JRE_{knee}	7.66	0.008*	0.13
			Group* $JRE_{ankle} §,***$	0.00	0.938	0.00
			Group	25.49	<0.001*	0.30
			$JRE_{hip} §,*****$	0.73	0.397	0.01
			$JRE_{knee} §,*****$	1.21	0.277	0.02
Sensory orientation	69.8±13.4	97.4±3.8	JRE_{ankle}	8.36	0.005*	0.12
			Group* $JRE_{hip} §,****$	1.45	0.234	0.03
			Group* $JRE_{knee} §,***$	0.52	0.473	0.01
			Group* $JRE_{ankle} §,**$	0.40	0.528	0.01
			Group	4.61	0.036	0.08
			JRE_{hip}	6.34	0.015	0.11
Stability in gait	59.1±13.9	92.3±6.4	$JRE_{knee} §,****$	1.42	0.238	0.03
			$JRE_{ankle} §,*****$	3.84	0.055	0.07
			Group* JRE_{hip}	10.13	0.002*	0.16
			Group* $JRE_{knee} §,*****$	1.83	0.182	0.04
			Group* $JRE_{ankle} §,**$	0.53	0.470	0.01
			Group	4.35	0.042	0.07
			JRE_{hip}	1.13	0.293	0.02
			$JRE_{knee} §,*****$	1.87	0.177	0.03
			$JRE_{ankle} §,****$	0.99	0.323	0.02
			Group* JRE_{hip}	9.11	0.004*	0.14
			Group* $JRE_{knee} §,***$	2.08	0.155	0.04
			Group* $JRE_{ankle} §,**$	0.20	0.655	0.00

JRE: joint reproduction error; F: F-statistic obtained from final General Linear Model; η^2p : partial eta squared, with 0.01-0.059: small; 0.06-0.13: medium and ≥ 0.14 =large effect.
 *P values marked indicating statistical significance (P<0.01), after §non-significant interaction terms and main effects were stepwise **, ***, ****, *****removed from final model.

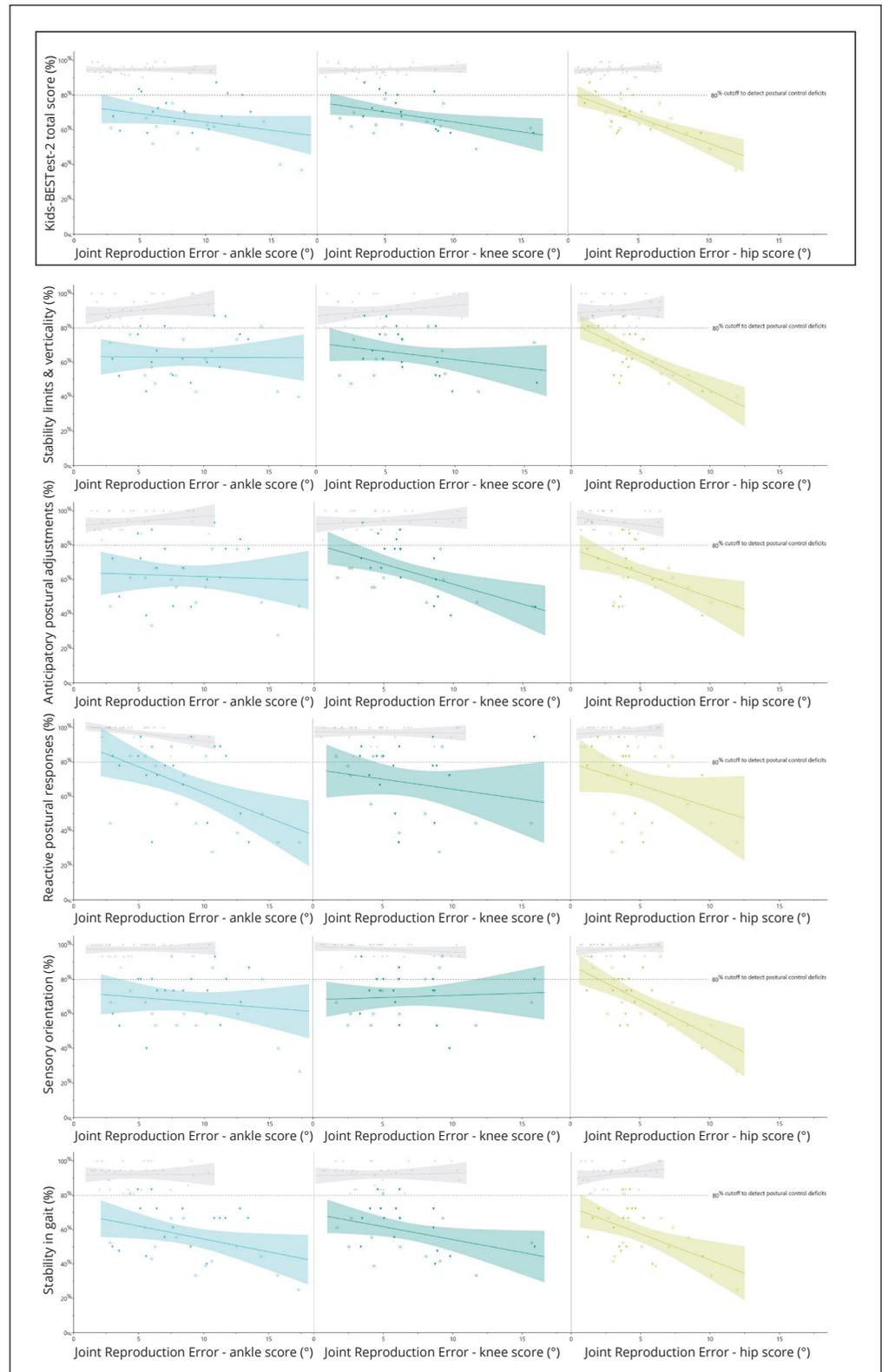


Figure 2.—Association between balance performance and joint-specific lower limb proprioception (JRE_{hip}, JRE_{knee} and JRE_{ankle}). Scatterplots of Kids-BESTest-2 total and domain (%) scores by absolute Joint Reproduction Error (JRE) values (°) for spastic unilateral CP (▼, N.=17), bilateral CP (◇, N.=12) and TD children (x, N.=29) aged 5 to 12 years. The JRE_{total} (data point) represents the sum of JRE values for dominant and non-dominant sides of the hip (JRE_{hip}=light green), knee (JRE_{knee}=dark green) and ankle (JRE_{ankle}=light blue) separately. Higher values correspond to poorer proprioception. Depending on age category, 28 to 36 Kids-BESTest-2 items were summed to produce a total score and 5 domain scores (%). A score of <80% cut off (---) indicates postural control deficits, with lower percentages reflecting poorer balance performance. Separate regression lines are shown for each group (CP=—; TD=- -) with the shaded band representing the 95% confidence interval in CP (color) and TD group (grey).

experiences difficulties with postural control and in which tasks these difficulties manifest.

The role of proprioceptive feedback underlying different postural control systems

In line with previous studies, children with CP experienced difficulties with tasks involving movement toward their limits of stability (*e.g.*, forward reaching),²⁶ postural transition from one body position to another (*e.g.*, alternating stair touch),³⁸ maintaining stability under altered sensory conditions (*e.g.*, standing with eyes closed)⁶ and during gait.⁵ All these tasks require subtle shifts of the COM in anticipation of a voluntary upper or lower limb movement to counteract its potentially destabilizing effect, a process known as anticipatory postural adjustments.¹³ To do so effectively, the brain uses internal models, which predict the sensory consequences of movement (feedforward control) based on prior experience and real-time sensory input (feedback-based control).¹¹ However, when proprioception is impaired, as observed in our study, a CP child's ability to perceive and integrate this sensory information may become compromised. This limits the brain's ability to accurately build and refine internal models, resulting in delayed or absent APAs^{14, 18, 38} and consequently, reduced stability during the task, and in some cases, slower task performance.³⁸ This aligns with recent neuroimaging evidence showing that proprioceptive processing in CP is characterized by abnormal cortical activation,³⁹ and that microstructural abnormalities in the corpus callosum and transcallosal lower-limb sensorimotor tracts, which are required for such processing, are directly associated with poorer postural control in adolescents with CP and their TD peers.⁴⁰ However, as a compensatory strategy, children with CP may rely more heavily on slower feedback-based control mechanisms. While this may be sufficient in easy task conditions (*e.g.*, standing with eyes open), it proves less effective as task complexity increases (*e.g.*, rise to toes or single leg stance) or under more high-demand sensory conditions (*e.g.*, standing with eyes closed), as observed in our study. In addition to impaired feedforward control, proprioceptive deficits also hinder the rapid and reliable use of feedback-based control in response to externally induced perturbations. As a result, children with CP may exhibit delayed, insufficient, and poorly coordinated postural responses, as evidenced both in our study and in previous work.^{15, 41} Following this, one might assume that more severe and/or widespread proprioceptive deficits, reflected by a higher JRE_{total} , would correspond to greater difficulties in postural control across multiple underlying

systems. Yet, the absence of a significant association in our findings suggests that JRE_{total} may not, on its own, fully explain the variability in children's overall and domain-specific balance performance (Figure 1). While it offers a complementary measure of a child's overall proprioceptive functioning, increases in JRE_{total} can arise from impairments at different joints (hip, knee, or ankle), each of which may impact postural control in distinct ways. For instance, two cases showed similar JRE_{total} scores (CP, GMFCS I: 7-year-old=20.55°; 8-year-old=20.49°), but in one case, this was primarily determined by poorer hip proprioception (JRE_{hip} : 8.45°, JRE_{knee} : 4.17°; JRE_{ankle} : 7.89°), while in the other case, the ankle was more affected (JRE_{hip} : 3.76°, JRE_{knee} : 5.05°, JRE_{ankle} : 11.70°). Although their overall proprioceptive functioning was nearly identical, their balance performance differed markedly: the CP child with predominant hip proprioception deficits experienced more difficulties in the domains of 'Stability Limits and Verticality' (52%), 'Transitions and Anticipatory Postural Adjustments' (56%) and 'Sensory orientation' (53%), while the child with poorer ankle proprioception performed notably better in these domains (87%, 78%, and 80%, respectively). This suggests that, beyond the overall severity, the distribution of the proprioceptive deficits, particularly at the hip, may have a more pronounced impact on a child's postural control.

Joint-specific contributions to different systems underlying postural control

Hip proprioception

A child's ability to reproduce hip joint positions was significantly associated with all postural control systems assessed by the Kids-BESTest-2, except for reactive responses. Depending on the specific system evaluated and the joint(s) involved in the postural demands of the task, these associations may be predominantly task- or pathology-dependent. For instance, during quiet standing, postural control is typically maintained through an ankle strategy, in which the body acts as an inverted pendulum around the ankles.¹⁰ The critical role of ankle proprioception in this strategy has been demonstrated by studies showing that vibration of the calf muscles (mimicking a forward sway) elicits compensatory backward sway through reflexive calf muscle activation in healthy individuals.⁴² In contrast, more challenging tasks, such as single leg stance or rising onto the toes, reduce the base of support and constrain the limits of stability, thereby increasing postural demands. To maintain stability under these conditions, postural control

strategies must extend beyond the ankle and involve more proximal segments, particularly the hip.⁴³ However, when hip proprioception is impaired, as observed in children with CP, or not yet fully matured, as may be the case in younger TD children,²¹ the effectiveness of such hip strategies may be compromised. This can lead to observable signs of instability, such as exaggerated trunk movements, which are reflected in lower scores on related Kids-BESTest-2 items. Moreover, in children with CP, more pronounced impairments in hip proprioception further compromised the effective use of hip strategies to approach stability limits in standing and sitting. Accordingly, poorer hip joint position reproduction was significantly associated with lower scores in the domain of “Transitions and Anticipatory Postural Adjustments” across both groups, and with “Stability Limits & Verticality” in the CP group, supporting a task-specific association between immature or impaired hip proprioception and reduced postural control in both domains.

Given the established role of ankle proprioception in postural control during quiet standing,^{10, 42} one might expect it to be a key determinant in the ‘Sensory orientation’ domain, which also involved quiet standing under similar sensory conditions. However, our findings suggest otherwise: children with CP and impaired ankle proprioception could still perform age-appropriately, whereas those with poorer hip proprioception experienced greater difficulties in maintaining balance (Figure 2). This underscores the role of proprioceptive reweighting, a process in which the CNS adjusts the weighting of sensory input within the proprioceptive system based on the reliability of its origin. For instance, when ankle proprioception becomes less reliable (e.g., standing on an unstable surface with eyes closed), healthy individuals adapt by increasing reliance on proximal proprioceptive input, particularly from the hip and trunk. This is evidenced by studies showing greater reflexive compensatory sway in response to multifidus muscle vibration compared to calf muscle vibration under such conditions.⁴² Given the frequent and often severe impairments in ankle proprioception among children with CP,²¹ the CNS may already shift weighting toward the non- or less affected hip, even under low-demanding sensory conditions (e.g., standing on a stable surface with eyes open). However, if hip proprioception is also (more severely) affected, this compensatory proprioceptive reweighting is likely compromised, leading to postural control difficulties in both standing, under low- and high-demanding sensory conditions, and walking, as observed in our study and in previous work.²³ This hypothesis offers a plausible ex-

planation for why prior fMRI work in adolescents with CP found no significant association between cortical responsiveness to passive ankle movement and postural control during similar tasks.³⁹ If the CNS down-weights unreliable ankle input in favor of proximal sources, the functional coupling between ankle-related cortical proprioceptive processing and postural control would indeed be diminished. Consequently, this suggests a pathology- rather than task-dependent association, which may also help explain the discrepancies in previous studies using similar postural control tasks. For instance, some studies reported increased sway under eyes-closed conditions⁴⁴ or decreased gait stability at higher walking speeds,⁴⁵ while others did not,^{46, 47} potentially due, in part, to variation in population characteristics, of which hip proprioceptive functioning might be one contributing factor.

Taken together, this suggests that better hip proprioception is a key contributor to a child’s ability to select mature or compensatory postural control strategies to maintain stability during voluntary-induced postural tasks. However, as this study relied on a clinical, observation-based evaluation of balance performance, future research should include quantitative analyses of COM dynamics to better capture the postural control strategies used by children during these tasks.

Knee proprioception

Our findings further suggest a potential pathology-dependent association between knee proprioception and postural control in the domain of ‘Transfers and Anticipatory Postural Adjustments,’ though this may be predominantly confounded by co-occurring primary (e.g., spasticity) and secondary (e.g., reduced range of motion) symptoms commonly observed in children with CP. Specifically, children with more severe CP often present with increased spasticity of hamstrings muscles and secondary musculoskeletal complications, such as knee joint contractures.⁴⁸ These factors may not only impair proprioceptive performance during the knee JPR task (by disrupting muscle spindle sensitivity),⁴⁹ but may also interfere with anticipatory postural adjustments and the movement execution required for tasks in this domain, such as accurately and rapidly lifting the foot onto the stair during alternating stair touching.³⁸

Ankle proprioception

Poorer ankle proprioception in both CP and TD children was significantly associated with more difficulties in eliciting appropriate ‘Reactive Postural Responses’ to

unexpected perturbations in forward, backward or lateral directions. Unlike in other domains, where children with CP with poorer ankle proprioception were able to compensate through proximal proprioceptive reweighting, this strategy proved insufficient for detecting and reacting to body sway during perturbations in this domain, as the predominant source of proprioceptive input comes from the ankles.¹¹ Consequently, children may rely more on other sensory modalities, such as vision, although visual feedback is delayed due to its longer supraspinal feedback loop (approximately 100 ms)⁵⁰ and less available during perturbations that induce backward sway. These two (out of five) tasks, in particular, were more challenging and performed with greater difficulty by both groups. In line with these findings, previous studies have reported that children with CP often fail to adequately restore their balance following external perturbations, showing delayed, insufficient and uncoordinated muscle responses.^{15, 19} Interestingly, Crenshaw *et al.* (2020) found no altered muscle response timing, magnitude or coordination during similar tasks,⁴¹ possibly reflecting differences in ankle proprioception across study populations. In TD children, the task-specific nature of this association may be due to the still-developing precision of ankle proprioception in younger children.²¹ These children may not yet efficiently engage proprioceptive feedback-based systems, leading to less effective in-place responses and a quicker tendency to rely on stepping responses for small perturbations compared to older children.⁴¹

Clinical implications

Children with CP experience postural control deficits across multiple underlying systems, all of which were associated with joint-specific proprioceptive impairments at the level of the hip, knee or ankle. These findings highlight the importance of considering lower limb proprioception as a potential underlying factor when evaluating and targeting deficient postural control systems in children with CP (using the Kids-BESTest-2 assessment as recommended⁷). Interventions that facilitate or alter proprioceptive input during functional, task-oriented balance training⁵¹ may enhance children's ability to perceive and integrate proprioceptive feedback, improving postural control. Further research should investigate whether training in such task-specific and sensory-enriched contexts can lead to improvements in proprioception and shifts in postural control strategies, and whether the extent of proprioceptive deficits may limit the effectiveness of such interventions.

Limitations of the study and future directions for research

A limitation of this study is the lack of subgroup analyses between children with unilateral (N.=17) and bilateral CP (N.=12), due to the relatively small sample sizes in each subgroup and statistical power limitations. Given the more severe and proximal motor involvement typically seen in bilateral CP,⁴⁸ one may consider that this is accompanied by more pronounced proprioceptive and postural control deficits, potentially confounding the observed association. Proprioceptive deficits in unilateral CP, however, appear equally prevalent and severe (as previously observed²¹), and data in both groups visually align around a shared negative trend between JRE and Kids-BESTest-2 balance performance (Figure 1, 2). This raises the need for future studies to disentangle whether the observed association reflects a true sensorimotor relationship or is primarily driven by group-level differences in motor severity. Additionally, beyond differences in topography, the current sample included children with various types of brain lesions, with the majority (69%) presenting with periventricular white matter (PWM) lesions. Although children with PWM lesions tend to develop better gross motor function,⁵² whether this extends to postural control remains unclear and warrants further investigation. Besides, another methodological limitation is that JPR was assessed within a single movement plane and direction per joint, whereas postural control strategies typically rely on bidirectional joint movements across multiple planes.¹¹ However, prior research has reported similar associations with postural control using JPR assessments in other planes (*i.e.*, transverse plane)²³ or directions (*i.e.*, plantar flexion),²⁵ suggesting a joint-specific contribution of lower limb proprioception that appears independent of the specific movement direction or plane assessed. Nevertheless, while JPR tasks offer valuable insights into proprioception as a separate construct,³⁵ they primarily engage conscious proprioceptive processing (*i.e.*, dorsal column-medial lemniscus pathway) and may not fully reflect subconscious proprioception (*i.e.*, spinocerebellar tracts) involved in postural control. To further extend these findings, future research should incorporate postural sway analysis combined with muscle vibration stimulation to better understand how children with CP adapt their proprioceptive reweighting strategies during postural control in task-specific contexts, compared to age-matched TD children. This is particularly relevant, as our current interpretation of task-specific or compensatory strategy shifts (*e.g.*, ankle vs. hip reliance) relied solely on joint-specific associations between JRE-based proprioceptive measures and clinical balance scores

(Kids-BESTest-2), which are observational and ordinal in nature. Although these clinical scores account for age- and task-specific constraints and have demonstrated concurrent validity with laboratory-based balance measures for specific domains,^{31, 32} further concurrent kine(ma)tic analyses are required to verify the strategy shifts proposed in this study and validate the remaining domains. Finally, although the current findings suggest that associations between proprioception and postural control are predominantly either task- or pathology-dependent, it is likely that both factors interact in determining postural control. For instance, difficulties in approaching stability limits and reactive stepping responses may be influenced not only by impairments in hip and ankle proprioception (depending on the task), but also by co-occurring vestibular dysfunction,⁵³ and increased ankle plantar flexor spasticity with agonist-antagonist co-activation¹⁷ (depending on the individual pathology), respectively. Similarly, poorer postural control in tasks requiring APAs have been associated with hip abductor weakness³⁸ and reduced selective motor control,⁵⁴ in addition to the hip proprioceptive deficits identified in our cohort. Furthermore, related components of this neuromuscular cluster, such as hip flexor spasticity and contractures, may also have contributed to the observed postural control deficits, thereby compounding the impact of the identified proprioceptive limitations, although this has not yet been investigated. Further research is therefore needed to integrate these sensorimotor profiles into multivariate models to disentangle how the presence of these additional deficits influences the proposed association between lower limb proprioception and postural control.

Conclusions

This study shows that postural control deficits in children with CP involve multiple underlying systems, each associated with joint-specific proprioceptive impairments in a task- and pathology-dependent manner. From a task-dependent perspective, impaired or immature proprioception may hinder postural control in tasks that rely on proprioceptive input from the affected joint to guide the necessary postural control strategy. For instance, ankle proprioception is crucial for ankle strategies during in-place perturbations, while hip proprioception supports hip strategies when approaching stability limits. From a pathology-dependent viewpoint, the ability to compensate for impairments at one joint (such as the ankle) by reweighting proprioceptive input from others (such as the hip), may be limited in CP, particularly when hip proprio-

ception is affected, further complicating postural control during standing and walking. Therefore, the distribution of proprioceptive deficits, rather than their overall severity, may be critical in understanding postural control deficits in this population. Future research should investigate how proprioceptive reweighting strategies are affected by these deficits and whether this can be improved through task-specific balance training in sensory-enriched contexts.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors' contributions

Pieter Meyns, Ann Hallems, Kaat Desloovere, Els Ortibus and Nina Jacobs conceived and designed the study experiments; Nina Jacobs performed the patient's recruitment, data acquisition and analysis; Ann Hallems contributed to the coding; Nina Jacobs wrote the manuscript; Pieter Meyns, Ann Hallems, Kaat Desloovere, Els Ortibus and Evi Verbecque contributed in interpreting of the data and in revising the manuscript. All authors read and approved the final version of the manuscript.

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History

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SUPPLEMENTARY DIGITAL MATERIAL 1

Supplementary Table I.—The degree of multicollinearity among covariates.

		Covariates			Response variable	
		JRE _{hip}	JRE _{knee}	JRE _{ankle}	Age	Kids-BESTest-2 (%)
JRE _{hip}	Correlation coefficient	1	0.017	0.395	-0.222	
	P value		0.899	0.002	0.090	
	VIF					1.077
JRE _{knee}	Correlation coefficient	0.017	1	0.201	-0.092	
	P value	0.899		0.128	0.489	
	VIF					1.025
JRE _{ankle}	Correlation coefficient	0.395	0.201	1	-0.139	
	P value	0.002	0.128		0.282	
	VIF					1/103

VIF = Variance Inflation Factor values for covariates included in General Linear Model analyses (JRE_{hip}, JRE_{knee}, JRE_{ankle}). Correlation coefficient = Pearson (r) for partial correlations between each covariate and age. P-values marked in **bold** indicate statistical significance ($p < 0.05$).

VIF values below 5 and correlation coefficients (r) below the 0.7–0.8 threshold^[35] are generally considered acceptable, indicating no multicollinearity concerns among covariates.

SUPPLEMENTARY DIGITAL MATERIAL 2

Supplementary Table II.—Pairwise correlations across all dependent variables.

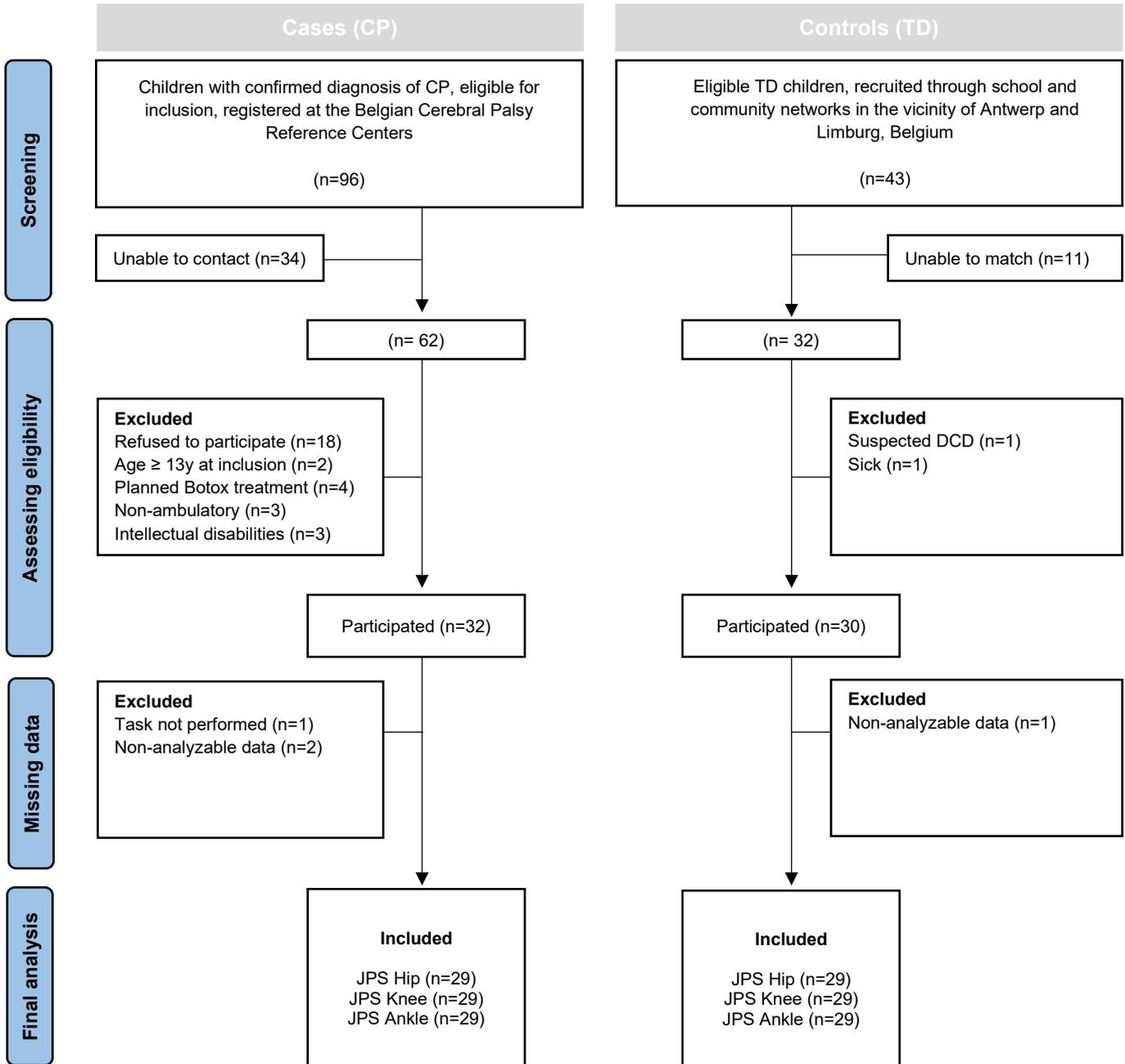
		Kids-BESTest-2 (%)					
		Total	Domain 2	Domain 3	Domain 4	Domain 5	Domain 6
Total	Correlation coefficient	1	0.889	0.887	0.751	0.873	0.935
	P value		<0.001	<0.001	<0.001	<0.001	<0.001
Domain 2	Correlation coefficient	0.889	1	0.800	0.521	0.766	0.783
	P value	<0.001		<0.001	<0.001	<0.001	<0.001
Domain 3	Correlation coefficient	0.887	0.800	1	0.513	0.779	0.806
	P value	<0.001	<0.001		<0.001	<0.001	<0.001
Domain 4	Correlation coefficient	0.751	0.521	0.513	1	0.525	0.681
	P value	<0.001	<0.001	<0.001		<0.001	<0.001
Domain 5	Correlation coefficient	0.873	0.766	0.779	0.525	1	0.794
	P value	<0.001	<0.001	<0.001	<0.001		<0.001
Domain 6	Correlation coefficient	0.935	0.783	0.806	0.681	0.794	1
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	

Domain 2 = Stability Limits/Verticality; Domain 3 = Anticipatory Postural Adjustments; Domain 4 = Reactive Postural Responses; Domain 5 = Sensory Orientation; Domain 6 = Stability in Gait
Correlation coefficient = Pearson (r) for pairwise correlations between the dependent Kids-BESTest-2 variables.

P-values marked in bold indicate statistical significance ($p < 0.05$).

SUPPLEMENTARY DIGITAL MATERIAL 3

Supplementary Table III—Participant recruitment and selection process.



SUPPLEMENTARY DIGITAL MATERIAL 4

Supplementary Table IV.—Descriptive statistics for lower limb proprioception and postural control – full sample (n=62).

	CP			TD			p-value
	Mean (SD) or Median (IQR)	/min-max	n	Mean (SD) or Median (IQR)	/min-max	n	
Lower limb proprioception (JPR)							
JRE _{total} (°)	19.6 (5.4)	/ 10.3-31.2	29	12.6 (3.7)	/ 7.2-19.1	29	<0.001 ^a
JRE _{hip} (°)	4.1 (2.8)	/ 1.2-12.0	30	2.9 (2.9)	/ 0.7-6.4	29	0.005 ^b
JRE _{knee} (°)	6.2 (4.6)	/ 1.7-15.9	29	4.4 (3.4)	/ 0.6-10.5	30	0.016 ^b
JRE _{ankle} (°)	8.6 (3.7)	/ 2.8-17.3	32	4.6 (2.5)	/ 1.4-10.4	30	<0.001 ^a
Postural control (Kids-BESTest-2)							
Total (%)	65.9 (11.6)	/ 36.9-87.1	32	94.5 (2.8)	/ 89.3-99.0	30	<0.001 ^a
Biomechanical constraints (%)	87.0 (11.5)	/ 53.0-93.0	32	100 (1.8)	/ 93.0-100	30	<0.001 ^b
Stability limits & verticality (%)	62.0 (23.3)	/ 40.0-87.0	32	90.0 (19.0)	/ 76.0-100	30	<0.001 ^b
Anticipatory postural adjustments (%)	61.0 (31.0)	/ 28.0-93.0	32	94.0 (11.0)	/ 80.0-100	30	<0.001 ^b
Reactive postural responses (%)	75 (38.9)	/ 27.8-94.4	32	100 (5.6)	/ 83.3-100	30	<0.001 ^b
Sensory orientation (%)	70.0 (25.3)	/ 27.0-93.0	32	100 (7.0)	/ 87.0-100	30	<0.001 ^b
Stability in gait (%)	55.7 (22.2)	/ 25.0-83.3	32	94.4 (10.7)	/ 81.0-100	30	<0.001 ^b

^a result of an independent samples t test with data presented as mean (SD);

^b result of a Mann-Whitney U-test with data presented as median (IQR);