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Faculteit Revalidatiewetenschappen

master in de revalidatiewetenschappen en de kinesitherapie

Masterthesis

Effect of exercise-induced lower limb muscle fatigue on lower limb proprioception and postural control in children with cerebral palsy and typically developing children

Britt Cauwenberghs

Scriptie ingediend tot het behalen van de graad van master in de revalidatiewetenschappen en de kinesitherapie, afstudeerrichting revalidatiewetenschappen en kinesitherapie bij musculoskeletale aandoeningen

PROMOTOR :

Prof. dr. Pieter MEYNS

BEGELEIDER :

Mevrouw Nina JACOBS



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Research context

Situated within the broader field of 'Balance & Gait', this thesis contributes to a larger ongoing PhD project led by Mrs. Jacobs Nina, titled 'Understanding balance control in children with cerebral palsy on central and peripheral level: a synergistic approach using neuromechanics, brain imaging and functional assessment' (project code: 92836). This PhD project was started in November 2021, and approved by the Committee for Medical Ethics (CME) of Antwerp University Hospital (UZA) / University of Antwerp (UAntwerpen), CME of Hasselt University (UHasselt) and the Ethics Committee Research UZ / KU Leuven (B3002021000145). Funding for this research was provided by Fonds Wetenschappelijk Onderzoek - Vlaanderen (FWO).

The goal of the PhD project is to gain a better understanding of the underlying causes of balance problems in children with cerebral palsy (CP), focusing on both central (brain lesions and proprioception) and peripheral factors (muscle fatigue due to physical activity). By combining neuromechanical analysis, brain imaging, and functional balance assessments, the study seeks to explore how these central and peripheral determinants contribute to impaired balance control, with the ultimate goal of improving treatment and training approaches.

This study aims to investigate the effects of lower limb muscle fatigue, induced by multi-joint weight-bearing exercise, on hip and ankle proprioception and postural control in children with CP compared to typically developing children. In agreement with Mrs. Jacobs Nina, the following research questions were formulated:

1. Effect of lower limb muscle fatigue, induced by multi-joint weight-bearing exercise, on postural control in children with CP compared to typically developing children
2. Effect of lower limb muscle fatigue, induced by multi-joint weight-bearing exercise, on hip and ankle proprioception in children with CP compared to typically developing children

This quasi-experimental study was conducted between May 2022 and October 2024 at the Multidisciplinary Motor Centre Antwerp (M2OCEAN, University of Antwerp), the Gait Real-time Analysis Interactive Lab (GRAIL, Hasselt University) or the Clinical Motion Analysis Laboratory (CMAL, University of Leuven).

Vicon, a laboratory-based optoelectronic motion capture system, was used for 3D movement analysis. All data collection and processing was performed by Mrs. Jacobs Nina using Vicon Nexus Software (v2.12.1; Vicon Inc.) and MATLAB (R2022a). To measure the center of pressure data, a force plate (AMTI, Watertown, USA) at a sampling frequency of 1000 Hz was used.

All three authors actively helped with recruitment and frequently assisted with assessments. Güney Umut assisted with labeling in Vicon Nexus Software for proprioception data, while Cauwenberghs Britt and Dierckx Brent assisted with processing the postural control data in Vicon Nexus Software and MATLAB.

The introduction and method was drafted collectively. Dierckx Brent and Güney Umut processed the feedback on the introduction, while Cauwenberghs Britt processed the feedback on the method. The refinement on both sections was carried out as a group. The results, discussion and conclusion were written collectively. Tables and figures were prepared and formatted by Cauwenberghs Britt and Güney Umut.

Mrs. Jacobs Nina provided written feedback twice on both the introduction and method, once on the results and twice on the final version of the thesis. Prof. dr. Meyns Pieter also gave written feedback on the final version once.

A total of five real-time meetings were held. Four meetings were held together with Mrs. Jacobs Nina, including an information session before the start of the thesis, two information sessions for the data analysis and one feedback session on the statistical analysis. A last meeting was held with Prof. dr. Meyns Pieter and Mrs. Jacobs Nina for final feedback on the thesis.

Effect of exercise-induced lower limb muscle fatigue on lower limb proprioception and postural control in children with cerebral palsy and typically developing children

Cauwenberghs Britt, Dierckx Brent, Güney Umut

ABSTRACT

Background: Cerebral palsy (CP) is a developmental motor disorder frequently accompanied by postural control and proprioception deficits. Muscle fatigue may worsen these deficits, but its impact is not fully understood.

Objectives: To assess muscle fatigue effects on postural control and proprioception.

Methods: Postural control and proprioception were assessed before and after muscle fatigue in 14 children with CP and 28 typically developing children (TDC). Postural control during blindfolded quiet standing was evaluated using center of pressure displacement (xCOP) and velocity (vCOP) in anteroposterior (AP) and mediolateral (ML) directions. Proprioception of the hip and ankle was assessed using a passive ipsilateral joint position reproduction (JPR) protocol by determining joint reproduction error (JRE). Muscle fatigue was obtained by an exercise-induced fatigue protocol.

Results: Post-fatigue, both groups showed significant increases in xCOP and vCOP in AP direction. Children with CP had significantly lower vCOP in AP direction and higher vCOP in ML direction compared to TDC. Moreover, children with CP showed higher xCOP in ML direction than TDC. Proprioception deteriorated post-fatigue in both groups, as shown by a higher hip and ankle JRE. Additionally, CP children consistently exhibited higher JRE values than TDC.

Conclusion: Muscle fatigue has a similar negative impact on postural control and proprioception in children with CP and TDC, with CP showing poorer baseline performance. This highlights the need for therapeutic approaches, like functional power training, that address both baseline impairments and fatigue resilience.

Keywords: children, cerebral palsy, muscle fatigue, postural control, proprioception, center of pressure, joint reproduction error

1. Introduction

Cerebral palsy (CP) is the most common motor disability in childhood, affecting 1.6 to 3 children out of every 1000 births (Patel et al., 2024). It defines a group of permanent movement and posture disorders that limit activity and are linked to non-progressive abnormalities in the developing fetal or infant brain (Rosenbaum et al., 2007). Although CP is primarily characterized by motor impairments such as spasticity, muscle contractures, muscle weakness, and loss of selective motor control (Østensjø et al., 2004), it is accompanied by sensory deficits, which may contribute to impaired postural control (Pavão et al., 2014a).

Postural control is the ability to position the body appropriately in space to maintain stability and alignment by keeping the center of mass projected within the base of support (Shumway-Cook & Woollacott, 2011). Getting into and maintaining a stable position involves complex interactions between the sensory system - which gathers input from the visual, vestibular, and somatosensory systems - and the motor system (Barela et al., 2011; Pavão et al., 2013). Research indicates that children with CP experience difficulties in sensory processing, which might result in postural control deficits (Pavão et al., 2014a; Pavão & Rocha, 2016). Sensory processing refers to how the central and peripheral nervous systems handle sensory input to produce organized and adaptive responses (i.e., compensation through another sensory system when there is reduced input from the visual system). Within this process, sensory integration helps organize the input, which is detected and transmitted to the brain through sensory registration for appropriate reactions (Powers, 2013). Somatosensory impairments, such as proprioceptive deficits (Wingert et al., 2009), can disrupt the sensory input needed for effective sensory integration, leading to difficulties with postural control in sensory-challenging environments (Damiano et al., 2013).

Children with CP demonstrate greater proprioceptive impairments in both lower limbs compared to typically developing children (TDC) (Akkaya & Elbasan, 2020; Boyer et al., 2023; Jacobs et al., 2024; Wingert et al., 2009; Zarkou et al., 2021). Proprioception is the ability to integrate sensory signals to determine the position and movement of body segments in space (Han et al., 2015a; Han et al., 2015b). Proprioception is primarily gathered peripherally through specialized sensory receptors known as mechanoreceptors located in muscles, tendons, ligaments, joints, and skin. These receptors convert mechanical changes in the tissues, such as stretch, compression, tension, and shear forces, into electrical signals. These are then

transmitted to the central nervous system for processing. Proprioception plays a fundamental role in postural control, primarily by sensory information from the leg muscles. (Henry & Baudry, 2019; Marasco & De Nooij, 2022; Riemann & Lephart, 2002).

Additional stressors, such as muscle fatigue, can adversely affect proprioception and postural control. Muscle fatigue is defined as an exercise-induced decrease in maximal voluntary force coupled with an increased perception of effort (Enoka & Duchateau, 2007; Enoka & Stuart, 1992). Prior findings show that muscle fatigue impairs joint position sense (Abdin et al., 2020; Miura et al., 2004) and increases postural sway (Vitiello et al., 2016; Gribble & Hertel, 2004; Paillard, 2012).

Previous studies in children with CP have mainly focused on general muscular exercises such as walking or isolated, single-joint exercises such as leg extensions to induce muscle fatigue (Abdin et al., 2020; El-Azeim et al., 2019; Vitiello et al., 2016). Therefore, there is a clear need for new research employing a fatigue protocol that is both isolated and functionally relevant by predominantly targeting neuromuscular and high levels of peripheral muscle fatigue, across multiple lower-limb joints and under weight-bearing conditions, in order to maximally impact the proprioceptive systems involved in functional movement and postural control.

To our knowledge, no study has examined the impact of muscle fatigue induced by multi-joint, weight-bearing exercises - designed to fatigue several major lower limb muscles and reach the neuromuscular threshold (Boyas & Guével, 2011) - on proprioception and postural control in children with CP.

This study, therefore, aims to investigate the effects of lower limb muscle fatigue, induced by multi-joint weight-bearing exercise, on hip and ankle proprioception and postural control in children with CP compared to TDC. We hypothesize that significant muscle fatigue-related changes will occur in proprioception and postural control in both anteroposterior (AP) and mediolateral (ML) direction across both groups, with more pronounced changes in children with CP. Clarifying these effects in this population may help guide therapeutic interventions to address the possibly overlooked impact of fatigue, with the aim of improving daily functioning.

2. Methods

2.1 Experimental design

This quasi-experimental study was conducted between May 2022 and October 2024 at the Multidisciplinary Motor Centre Antwerp (M2OCEAN, University of Antwerp), the Gait Real-time Analysis Interactive Lab (GRAIL, Hasselt University) or the Clinical Motion Analysis Laboratory (CMAL, University of Leuven), depending on the region where the child was recruited. The study received ethical approval by the Committee for Medical Ethics (CME) of Antwerp University Hospital (UZA) / University of Antwerp, CME of Hasselt University and the Ethical Committee of University Hospital Leuven (UZ Leuven) / KU Leuven (B3002021000145). Written informed consent was obtained from the children's parents prior to participation. This study is part of a broader research examining the relationship between proprioception, brain lesion characteristics, and muscle fatigue with balance in CP.

2.2 Participants

Children aged between 5 years and 0 months and 12 years and 11 months were recruited through Cerebral Palsy Reference Centers from the UZA (CePRA) and UZ Leuven, private practices, regular and specialized elementary schools, sports clubs, as well as acquaintances and social media.

Children with CP were included if they met the following inclusion criteria: (1) confirmed diagnosis of CP, (2) spastic type, (3) unilateral or bilateral involvement according to the Surveillance of Cerebral Palsy in Europe (SCPE) classification (Cans, 2000), (4) Gross Motor Function Classification System (GMFCS) level I or II, indicating walking disabilities like a decrease in speed, balance and coordination impairments or difficulty with walking long distances and balancing on uneven surfaces, inclines, or in crowded areas (Paulson & Vargus-Adams, 2017); GMFCS level III indicating independently walking for six meters using assistive devices and standing independently for one minute and (5) cognitive capability of understanding verbal instructions. Children with CP who had undergone lower extremity surgery within the past year and/or received botulinum toxin injections within the past 12 weeks were excluded. TDC were matched to children with CP based on age and gender, and included using a 2:1 ratio, respectively. TDC were included if they met the following inclusion criteria: (1) born > 37 weeks of gestation and (2) intelligence quotient (IQ) ≥ 70 . They were

excluded if they had (1) neuromotor or neurodevelopmental disorders, e.g., developmental coordination disorder.

Comorbidities, i.e., autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD), were allowed in both CP and TDC groups to ensure a representative sample. Across both groups, children were excluded when (1) a general questionnaire completed by their parents indicated the presence of intellectual, orthopedic, medical, or behavioral conditions that might interfere with test performance (2) children had uncorrected visual or vestibular impairments.

2.3 Sample size calculation

The sample size was calculated based on previous findings by Abdin et al. (2020) regarding COP ML, COP AP, and JRE in children with CP. To detect significant differences with 80% power and a significance level (α) of .05, a minimum of 24 participants was required for COP ML (effect size = 0.61), 21 for COP AP (effect size = 0.66), and 12 for JRE (effect size = 0.93). The largest required sample size of 24 was used in this study. Power analysis was conducted in G*Power version 3.1.9.7 using a *t*-test model for the difference between two dependent means (matched pairs).

2.4 Materials and procedure

2.4.1 Exercise-induced fatigue protocol

To induce lower limb muscle fatigue, all children received verbal instructions to perform a series of two-legged, full-depth squats through their entire active range of motion at a fixed pace, which is considered feasible for children between 6 and 19 years old (Eken et al., 2016). Before the test, they performed a practice trial to familiarize themselves with the squat movement and to determine their maximal active range of motion (i.e., the lowest point that can be controlled), and a height-adjustable chair was positioned accordingly. Starting from an upright position, children were instructed to squat as deeply as possible, aiming for maximal knee and hip flexion while maintaining the trunk upright. Children maintained this depth by lightly touching the chair with their buttocks without sitting down before returning to the upright standing position. To standardize the repetitions per minute, a metronome was used at a pace of 40 beats per minute (bpm), resulting in a total squat cycle lasting two beats, the

first beat indicating the start of the descent and the second beat indicating the beginning of the ascent.

Throughout the test, an examiner stood in front of the child and held the child's hands to provide guidance and assist with balance. The examiner did not actively perform the squats but remained present to ensure safety, as children were instructed to not rely on the examiner for support. Additionally, the examiner provided verbal feedback to help the child keep pace with the metronome and complete the full range of motion during each squat.

Squat repetitions were not time- or repetition-fixed and were performed continuously without stopping. The task ended when (1) the child could no longer maintain sufficient performance for five consecutive squats (e.g., not reaching full range of motion and/or slowing pace below 40 bpm), even with maximum encouragement, or (2) volitional exhaustion occurred.

2.4.2 Data assessments

Postural control and lower limb proprioception were evaluated before and immediately after the exercise-induced muscle fatigue protocol.

2.4.2.1 Postural Control

a. Task

Children stood quietly for 40 seconds in a barefoot, bipedal stance while blindfolded. The position was standardized using landmarks on the force plate (ten centimeters inter-heel distance). They were instructed to stand as still as possible, keeping their arms on the hips. This corresponds to condition 2 of the Clinical Test of Sensory Interaction of Balance (CTSIB), aligned with item 2 of domain 5 ('Sensory Orientation') from the extended version of Balance Evaluation Systems Test for children (Kids-BESTest-2) (Johnson et al., 2024).

b. Outcome parameters

Simultaneously, postural sway was evaluated in terms of the Center of Pressure displacement (xCOP) in mm and velocity (vCOP) in mm/s in ML and AP direction, measured with a force plate (AMTI, Watertown, USA) at a sampling frequency of 1000 Hz (Lee & Sun, 2018). The mean of three trials was taken, which proved to be a representative measure of postural control (Ruhe et al., 2010). A higher mean xCOP or vCOP suggests decreased postural stability. Mean xCOP and vCOP can be used in both ML and AP directions (Chen et al., 2021; Palmieri et al., 2002).

c. Data signaling and processing

The xCOP was estimated by using the following equation: $COP_{ML}(t) = - (My(t) + Fx(t) * Oz)/Fz(t)$ and $COP_{AP} = - (Mx(t) + Fy(t)*Oz)/Fz(t)$ with My = moment about Y- axis based on ML force, Mx = moment about X-axis based on AP force, Fz = vertical ground reaction force and zero the offset of the geometric plate center. First, COP trajectories with AP and ML coordinates were calculated for each time point t , for the two sides independently. Subsequently, the net COP under the two limbs combined was calculated as a weighted average (using Fz) from the left- and right-sided COPs using the following formula: $COP_{net} = ((COP_{left} * Fz_{left}) + (COP_{right} * Fz_{right}))/ (Fz_{left} + Fz_{right})$. Prior to processing, all COP data were filtered by using a Butterworth filter with a low-pass cut-off frequency of 12.5 Hz. After data filtering, the following stabilometric parameters were calculated based on COP_{net} : the difference between maximum and minimum xCOP (amplitude) (mm) and mean vCOP (mm/s), both in AP and ML direction. Only the last 30 seconds of each trial were considered to obtain solely steady-state balance measures (Lafond et al., 2004; Clair & Riach, 1996). Data filtering and processing were performed in MATLAB R2022a using custom-made codes.

2.4.2.2 Proprioception

a. Task

Proprioception was assessed for the ankle and hip joint on the non-dominant side using the passive ipsilateral joint position reproduction (JPR) protocol, as described previously in (Jacobs et al., 2025). The non-dominant leg was defined as the one the child used while kicking a ball, representing the limb not preferred to perform the balancing aspect of the task.

During the JPR tasks, children were seated on a treatment table with their legs relaxed and unsupported (90° of knee flexion), not wearing shoes or socks. The table fully supported the upper leg, and the arms were crossed over their chest. For the start position of the ankle JPR task, the examiner passively positioned the ankle in maximal plantar flexion. The starting position for the hip JPR task was the same, except the children sat on an inclination cushion on the treatment table without back support, creating the baseline position of 70° hip flexion. To ensure sufficient postural stability, the table was lowered until the child's feet were in contact with the ground.

In this JPR assessment, the examiner positions the child's limb at a predetermined target position using an inclinometer distally attached to the moving segment, approximately perpendicular to the flexion-extension axis. After experiencing and memorizing this position for five seconds, the child's limb was passively moved back to the neutral starting position. The child was then instructed to re-identify and match the target position (i.e., reproduction joint position) by pressing a button synchronized to motion capture software when the same limb was passively moved back into the same range. All JPR tasks were performed while children were blindfolded to eliminate visual input. The target positions were defined in the sagittal plane as follows:

Hip JPR task: 20° of flexion from an initial position of 70° hip flexion, resulting in a final hip flexion angle of 90°.

Ankle JPR task: 15° of dorsiflexion from an initial position of maximal plantar flexion, resulting in a final plantar flexion angle of 35°.

After familiarizing the protocol with at least one trial with and without vision, the ankle and hip JPR tasks were repeated three times for the non-dominant leg, resulting in six trials (one side × two joints × three repetitions). The order of the joints (ankle and hip) was randomized to minimize potential learning effects. All JPR assessments were conducted by the same trained examiner to minimize the random error induced by inter-rater variability and lasted twenty minutes in total.

b. Outcome

The absolute joint reproduction error (JRE) in degrees, representing the difference between target and reproduced joint angles, was measured using 3D kinematic data collected via a laboratory-based optoelectronic motion capture system (VICON, Oxford Metrics, Oxford, UK) with 10 high-speed infrared cameras operating at 100 Hz. Twenty-six 14mm Reflective markers were placed on the child's body according to specific anatomical landmarks defined by lower limb recommendations of the International Society of Biomechanics (ISB) (Wu et al., 2002). For each JPR task, the best JRE of three trials was taken. Jacobs et al. (2025) demonstrated that, in children, proprioception of the ankle and hip measured through passive JPR is more reliable and precise when using the best joint JRE rather than the mean JRE. The best JRE is the trial with the smallest JRE in absolute value.

c. Data signaling and processing

Hip and ankle joint angles were calculated using Vicon Nexus software (v2.12.1; Vicon Inc.). The JRE calculations were performed in MATLAB R2022a.

2.5 Statistical analysis

Statistical analyses were performed using JMP PRO (version 17.0, SAS Institute Inc., Cary, NC, USA). Data normality was assessed through visual inspection (histogram) and the Kolmogorov-Smirnov goodness-of-fit test. Homoscedasticity was tested with residuals by predicted plots and O'Brien tests. To investigate the effects of exercise-induced lower limb muscle fatigue on hip and ankle proprioception and postural control in children with CP compared to TDC, a two-way ANOVA for repeated measurements was performed. This statistical test was chosen because continuous data with influence of categorical variables with repeated measurements were examined. This ANOVA analysis was repeated six times for six dependent variables: hip JRE, ankle JRE, xCOP ML, xCOP AP, vCOP ML, and vCOP AP. In all the analyses, the independent variables were time (pre- and post-fatigue), group (CP and TDC), and the interaction effect between time and group. Subject ID was included as a random effect to account for individual variability between children and to control for repeated measurements within subjects. P-values < .05 were considered statistically significant.

In case of non-normally distributed data, a Box-Cox transformation was applied to normalize the skewed data. This method is only appropriate when the outcome variable is continuous and strictly positive, as these are necessary conditions for the mathematical validity of the transformation (Marimuthu et al., 2022).

No correction was applied if less than 10% of the data was missing. An average value was used to replace missing values in cases where the percentage of missing data exceeded 10%.

3. Results

3.1 Participants

42 children participated in this study, including 14 children with CP (5-12 years) and 28 TDC (5-12 years). The population characteristics are demonstrated in Table 1. Descriptive statistics of the means and standard deviations for each outcome variable are presented in Table 2.

Table 1

Population Characteristics

	CP (<i>n</i> = 14)	TDC (<i>n</i> = 28)	<i>p</i> -value
Age (years), M (SD)	8.97 (1.68)	8.71 (1.97)	.676a
Gender (male/female)	5/9	15/13	.275c
Height (cm), M (SD)	133.24 (12.37)	133.26 (12.17)	.995a
Weight (kg), M (SD)	30.32 (9.43)	30.33 (7.80)	.997b
BMI (kg/m ²), M (SD)	16.62 (2.50)	18.07 (3.32)	.135b
Dominant leg (left/right)	3/11	6/22	1.000d
GMFCS level (I/II)	11/3	-	-
Affected side (UL/BL)	7/7	-	-

Note. M = mean; SD = standard deviation; BMI = body mass index; GMFCS = Gross Motor Function Classification System; UL = unilateral; BL = bilateral; a = *t*-test; b = Welch's *t*-test; c = Chi-squared test; d = Fisher's exact test.

Table 2*Descriptive Statistics for Outcome Measures by Group and Time*

Outcome measure	Group	Pre-fatigue M (SD)	Post-fatigue M (SD)	Test statistic	p-value
Hip JRE (°)	CP	1.79 (1.33)	2.53 (1.40)	1.61	.138a
Hip JRE (°)	TDC	1.15 (0.71)	1.69 (1.04)	2.29	.031a
Ankle JRE (°)	CP	3.07 (1.85)	3.79 (2.90)	4.00	.791b
Ankle JRE (°)	TDC	1.49 (0.86)	2.13 (1.23)	2.17	.040a
xCOP ML (mm)	CP	67.61 (46.90)	98.89 (55.51)	2.21	.047a
xCOP ML (mm)	TDC	46.61 (33.15)	52.62 (46.59)	41.00	.360b
xCOP AP (mm)	CP	40.51 (16.14)	51.42 (34.43)	28.50	.048b
xCOP AP (mm)	TDC	44.65 (22.15)	49.77 (25.43)	69.00	.118b
vCOP ML (mm/s)	CP	24.22 (14.56)	28.55 (12.41)	1.16	.270a
vCOP ML (mm/s)	TDC	17.02 (11.89)	17.81 (12.64)	38.00	.397b
vCOP AP (mm/s)	CP	15.95 (6.14)	21.92 (13.64)	38.50	.005b
vCOP AP (mm/s)	TDC	24.35 (12.08)	28.71 (14.09)	89.00	.040b

Note. M = mean; SD = standard deviation; CP = Cerebral Palsy; TDC = typically developing children; JRE = joint reproduction error; xCOP = center of pressure displacement; vCOP = center of pressure velocity; ML = mediolateral; AP = anteroposterior; a = paired *t*-test; b = Wilcoxon signed-rank test; bolt = significant difference ($p < .05$).

Table 3

Results of Two-Way ANOVA for Repeated Measurements for Effects of Group, Time, and their Interaction on Joint Reproduction Error and Center of Pressure Parameters

Dependent variable	Independent variable	F-value	p-value
Hip JRE	Group	$F_{(1,35)} = 6.55$	.015
	Time	$F_{(1,36)} = 7.23$	.011
	Group x time	$F_{(1,35)} = 0.05$	.825
Ankle JRE	Group	$F_{(1,36)} = 8.36$	.007
	Time	$F_{(1,37)} = 5.59$	.023
	Group x time	$F_{(1,36)} = 0.87$	.357
xCOP ML	Group	$F_{(1,39)} = 7.71$	.008
	Time	$F_{(1,40)} = 4.05$	.051
	Group x time	$F_{(1,39)} = 0.10$	.103
xCOP AP	Group	$F_{(1,39)} = 0.05$	.832
	Time	$F_{(1,40)} = 5.46$	.025
	Group x time	$F_{(1,39)} = 0.11$	.746
vCOP ML	Group	$F_{(1,39)} = 7.82$	.008
	Time	$F_{(1,40)} = 1.64$	.208
	Group x time	$F_{(1,39)} = 0.86$	.359
vCOP AP	Group	$F_{(1,39)} = 6.35$	.016
	Time	$F_{(1,40)} = 13.92$	.001
	Group x time	$F_{(1,39)} = 1.20$	.280

Note. This table presents the F- and p-values for the main effects of group (CP/TDC), time (pre-/post-fatigue), and their interaction (group × time) on the following variables: hip and ankle JRE, xCOP ML, xCOP AP, vCOP ML and vCOP AP. JRE = joint reproduction error; xCOP = center of pressure displacement; vCOP = center of pressure velocity; ML = mediolateral; AP = anteroposterior; bolt = significant difference ($p < .05$).

3.2 Postural control

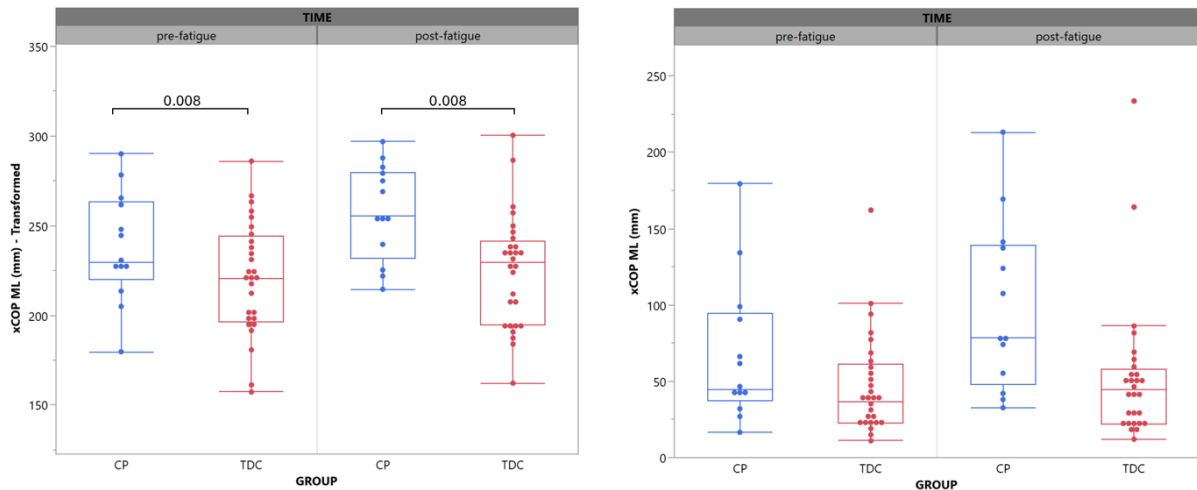
The results presented in Table 3 were obtained by conducting a two-way ANOVA for repeated measurements with the data transformed via Box-Cox, which were also used for interpretation. Missing data accounted for 1.59%, as one child with CP did not have postural control data. Therefore, no correction was applied.

3.2.1 COP displacement

No significant interaction effects between time and group were found in xCOP in both the ML and AP direction ($p > .05$). In ML direction, no significant effect of time was found ($p > .05$). A significant time effect was observed in AP direction, showing an increased xCOP post-fatigue ($p = .025$). A significant group effect was found only in ML direction, in which children with CP showed significantly higher xCOP than TDC ($p = .008$). Box plots with the transformed and original data for xCOP in ML and AP direction are shown in Figures 1 and 2.

Figure 1

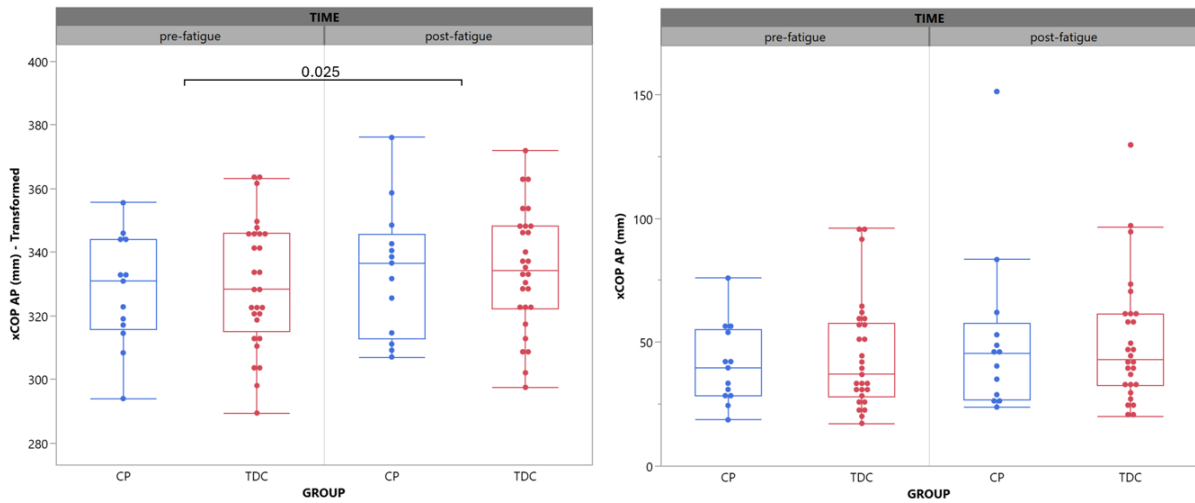
Box plots of Center of Pressure Displacement in Mediolateral Direction by Group and Time



Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; xCOP = center of pressure displacement; ML = mediolateral.

Figure 2

Box plots of Center of Pressure Displacement in Anteroposterior Direction by Group and Time



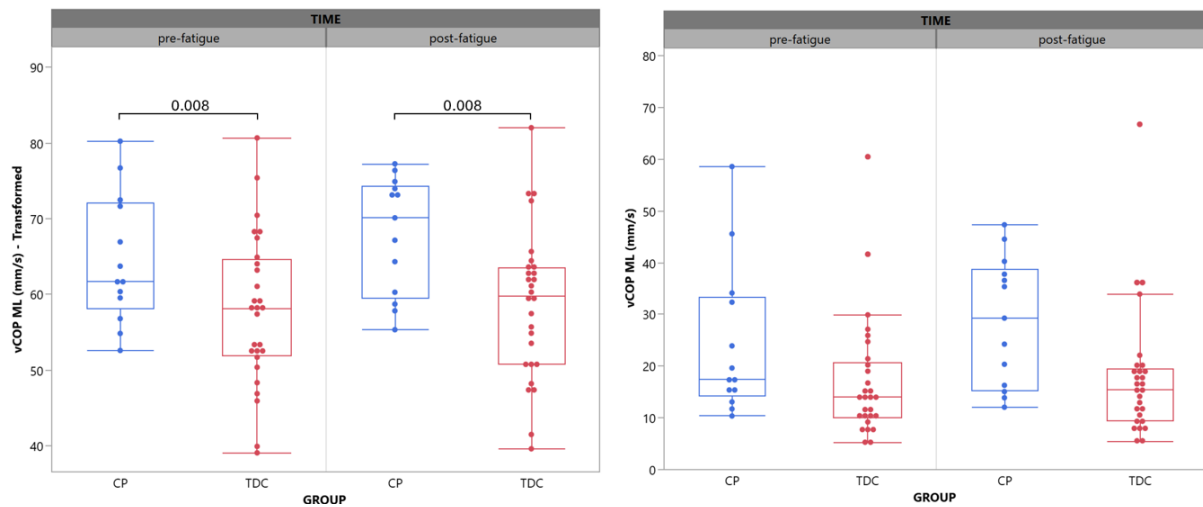
Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; xCOP = center of pressure displacement; AP = anteroposterior.

3.2.2 COP velocity

No significant interaction effects between time and group were found in vCOP in both ML and AP directions ($p > .05$). In ML direction, no significant effect of time was found ($p > .05$). A significant time effect was observed in AP direction, showing an increased vCOP post-fatigue ($p = .001$). In both ML and AP directions, a significant group effect was found. Children with CP exhibited a significantly higher vCOP compared to TDC in ML direction ($p = .008$) and children with CP exhibited a significantly lower vCOP than TDC in AP direction ($p = .016$). Box plots with the transformed and original data for vCOP in ML direction and AP direction are shown in Figures 3 and 4.

Figure 3

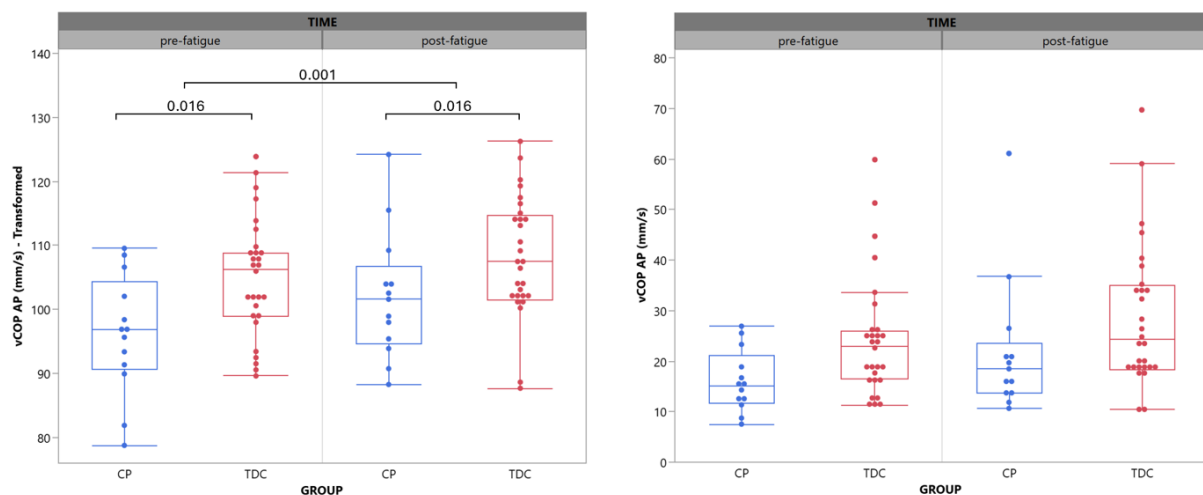
Box plots of Center of Pressure Velocity in Mediolateral Direction by Group and Time



Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; vCOP = center of pressure velocity; ML = mediolateral.

Figure 4

Box plots of Center of Pressure Velocity in Anteroposterior Direction by Group and Time



Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line

indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; vCOP = center of pressure velocity; AP = anteroposterior.

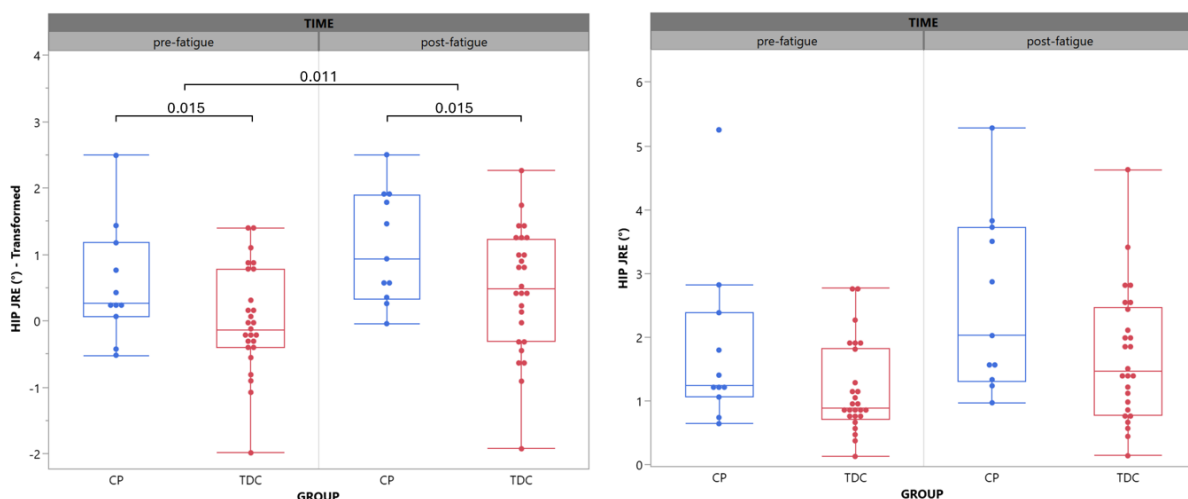
3.3 Lower limb proprioception

The results presented in Table 3 were obtained by conducting a two-way ANOVA for repeated measurements with the data transformed via Box-Cox, which were also used for interpretation. Missing data accounted for 3.57%, of which 1.98% in CP children and 1.59% in TDC. Therefore, no correction was applied.

For both the hip and ankle JPR tasks, no significant interaction effect between time and group was found in JRE ($p > .05$). Both for the hip and ankle JPR task, CP and TDC showed significantly higher JRE values post-fatigue, supporting a main effect of time (JRE hip: $p = .011$; JRE ankle: $p = .023$). Children with CP showed significantly higher JRE values when reproducing hip joint ($p = .015$) and ankle joint positions ($p = .007$) during JPR tasks. Box plots with the transformed and original data for hip JRE and ankle JRE are shown in Figures 5 and 6.

Figure 5

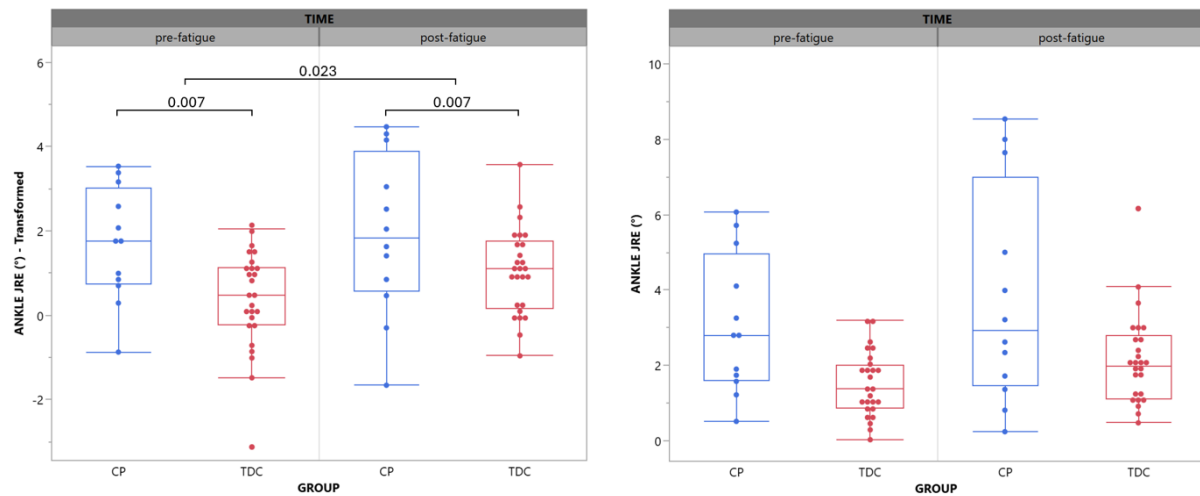
Box plots of Hip Joint Reproduction Error by Group and Time



Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; JRE = joint reproduction error.

Figure 6

Box plots of Ankle Joint Reproduction Error by Group and Time



Note. The left panel shows the transformed data (Box-Cox) with significance(s), the right panel shows the original data for illustration. Blue box plots represent the CP group and red box plots represent the TDC group. Each box represents the interquartile range, with the horizontal line indicating the median and dots representing individual data points. CP = Cerebral Palsy; TDC = typically developing children; JRE = joint reproduction error.

4. Discussion

This study aimed to assess lower limb muscle fatigue, induced by a multi-joint weight-bearing exercise (squatting), on proprioception of the hip and ankle and postural control in children with CP compared to TDC. It was hypothesized that both groups would experience significant decreases in proprioception and postural control following an exercise-induced muscle fatigue protocol, with a more pronounced effect expected in children with CP. While the results confirmed baseline differences between groups, the fatigue-induced changes were similar in magnitude across both groups, partially contradicting the initial hypothesis. The considerable inter-individual heterogeneity within the CP group may explain the absence of combined influences. Participants varied regarding motor impairment (unilateral vs. bilateral), GMFCS level (I–II), and functional capabilities. Such inter-individual variability likely influenced proprioceptive and postural control outcomes, possibly masking subgroup-specific effects. This underscores the need for personalized assessment and intervention approaches that accommodate the broad spectrum of motor function within the CP population (Jacobs et al., 2025).

4.1 Effect of fatigue

Exercise-induced muscle fatigue was associated with reduced proprioceptive accuracy in both groups, as reflected by an increased JRE post-fatigue. This aligns with earlier findings showing that proprioceptive input becomes less accurate after fatigue due to muscle damage, affecting the body's ability to perceive limb position and movement (Paschalis et al., 2007). In addition, Miura et al. (2004) found that fatigue can impair proprioception, likely due to compromised central processing of sensory information. Together, these findings suggest that both peripheral and central nervous systems contribute to the decline in proprioceptive accuracy following muscle fatigue for both CP children and TDC.

Static postural control also deteriorated following fatigue, with a larger amplitude and velocity of postural sway in AP direction. According to Paillard (2012), postural control worsens after muscle fatigue due to disruptions in sensory input and motor output. Muscle fatigue impairs the central nervous system's ability to process sensory information and generate effective motor responses. In terms of motor output, peripheral fatigue reduces muscle contractility (Gandevia, 2001) and reflex function (Laudani et al., 2009), while central fatigue results in

slower, less precise, and weaker motor responses that impair postural control (Paillard, 2012). These disruptions in sensory and motor function may explain the observed increase in postural sway amplitude and velocity in AP direction following fatigue.

Notably, ML postural control did not significantly deteriorate post-fatigue due to task characteristics (i.e., bipedal stance with ten centimeters inter-heel distance) that limited ML demands (Kirby et al., 1987), as well as the limited activation of the muscles, during squatting, which are primarily responsible for ML stability (Agarwal et al., 2021).

The observed differences in post-fatigue outcomes may be linked to the fact that matching the level of fatigue across participants posed a methodological challenge. Although the same squat frequency and termination criteria were used, individual fatigue thresholds likely varied. By pushing participants to maximum exhaustion, we minimized potential bias. However, differences in muscular endurance, perceived effort, and task execution among individuals, such as adopting a more forward-leaning posture or performing the movement on tiptoes, may have led to the termination of the task due to fatigue in other muscle groups.

Future research should not only explore the effects of fatigue on postural control and proprioception, but also investigate how quickly fatigue develops in this population and how children with CP adapt to it, for instance, by adopting alternative postural or movement strategies.

4.2 Group differences

Children with CP consistently showed poorer hip and ankle proprioception (reflected as higher JRE values) compared to TDC, measured by a passive ipsilateral JPR protocol. These findings align with previous literature highlighting impaired proprioceptive processing in CP, showing that these children experience difficulties with reproducing ankle (Zarkou et al., 2020) and hip joint positions (Wingert et al., 2009). These proprioceptive impairments might result from deficits in the thalamocortical pathways to the somatosensory cortex (Hoon et al., 2009; Nagae et al., 2007).

In terms of postural control, data from two COP variables (COP displacement and COP velocity) were collected in order to make a stronger statement. Children with CP and TDC showed a similar amplitude of postural sway in AP direction, while children with CP had a larger sway amplitude in ML direction. According to Winter et al. (1996), in a side-by-side stance, postural

control in the AP direction is predominantly controlled by the ankle plantar- and dorsiflexors. In contrast, children with CP have deficiencies in recruiting the muscles around the ankle joint (Degraaf-Peters et al., 2007; Ferdjallah et al., 2002; Nashner et al., 1983). Consequently, they tend to rely more on the hip strategy (Nashner et al., 1983). This strategy, which relies more on hip abductors and adductors, has been associated with increased ML displacements (Ferdjallah et al., 2002; Winter et al., 1996). This may explain the larger sway amplitude observed in the CP group in ML direction, but not in AP direction. Children with CP also showed a larger sway velocity in ML direction. The combination of both a larger sway amplitude and velocity could indicate poorer postural control in ML direction in children with CP (Chen et al., 2021; Palmieri et al., 2002). These findings are further supported by previous research, which similarly observed increased amplitude and velocity of postural sway in ML direction during quiet standing in children with CP, indicating challenges with ML postural control (Pavão et al., 2014b).

Regarding the AP postural sway velocity while standing, TDC showed a higher velocity than children with CP, which could be explained by a more dynamic ankle strategy to maintain postural control (Winter et al., 1996).

4.3 Strengths

This study has several notable strengths. First, the inclusion of age- and gender-matched TDC, thereby adding a control group, allowed for direct group comparison. This provided insights into both baseline differences and the relative effects of muscle fatigue on proprioception and postural control. This comparative approach enhances the clinical relevance of the findings and contributes to a more nuanced understanding of motor functioning in CP.

Second, the study employed a multi-joint, weight-bearing fatigue protocol, which more closely mimics fatigue during real-life functional activities such as walking or playing, thereby improving the validity of the experimental design (Eken et al., 2017). Previous studies often relied on isolated, single-joint protocols, which may not fully capture the complex interplay of fatigue and motor control in everyday tasks (Abdin et al., 2020; El-Azeim et al., 2019; Vitiello et al., 2016). Furthermore, this study used a non-time- or repetition-fixed fatigue protocol, which allowed for equal muscle fatigue in both groups (Eken et al., 2014).

Third, objective and high-precision measurement tools were used, including 3D motion capture for JRE and force plates for COP data (Jacobs et al., 2025; Huurnink et al., 2013). Additionally, two COP variables (COP displacement and COP velocity) in both ML and AP directions were analyzed, increasing the validity of the postural control assessment.

Furthermore, all measurements were conducted by the same investigator to reduce the risk of inter-rater bias.

Lastly, the study design included standardized testing procedures, fixed metronome pacing, and consistent examiner presence, which helped minimize variability and improve the reliability of the results.

4.4 Limitations

Several limitations must be acknowledged. Firstly, the sample size remained relatively small, which may have limited the power to detect subtle interaction effects or subgroup differences, as it was based on a minimum of 24 participants calculated from prior findings by Abdin et al. (2020) (see Section 2.3). Additionally, only one fatigue protocol (squatting) and one postural condition (bipedal standing with blindfold) were examined, limiting the generalizability of the findings to other types of fatigue-inducing activities and postural tasks (e.g., unipedal stance). Furthermore, subjective indicators of fatigue were used to determine task termination. Future studies could benefit from incorporating objective measures of muscle fatigue, such as electromyography (EMG), to identify muscle activation patterns and synergies involved during the task and to more accurately determine the onset and extent of neuromuscular exhaustion (Moll et al., 2022). Finally, this study included children with unilateral and bilateral CP, which provides considerable heterogeneity in this group. Future research could split unilateral and bilateral CP into two groups and compare them with a control group.

4.5 Clinical importance

Clinicians should be aware of the impact of fatigue on postural control and proprioception during therapy and daily life. The findings emphasize the importance of integrating both proprioceptive and postural control training into rehabilitation programs for children with CP, particularly targeting the hip and ankle under muscle fatigue conditions. Proprioceptive deficits in children with CP have been shown to contribute to postural control impairments, so interventions that address both aspects, such as weight-bearing tasks, joint matching

exercises, and postural control training, may be particularly effective in improving functional performance.

As suggested by previous research on CP therapy, task-oriented training is most beneficial in this context (Novak et al., 2013). During task-oriented functional postural control training, proprioceptive input can be facilitated, and sufficient repetition can be introduced to train under fatigue. In addition, Eken et al. (2018) suggested that clinicians and therapists should primarily focus strength training programs on lower leg muscles in order to reduce muscle fatigue during walking in children with CP. However, functional power training improved walking capacity and muscle strength more than conventional strength training. In this type of training, a higher movement velocity is used in the progressive loaded strength training exercises, and strength exercises are incorporated into functional movements like walking and sprinting. (Van Vulpen et al., 2017). Furthermore, incorporating rest breaks during training sessions is also important to manage fatigue and prevent further postural control and proprioception disruption.

5. Conclusion

This study demonstrates that exercise-induced lower-limb muscle fatigue has a similar relative impact on postural control and proprioception in children with CP and TDC. Although fatigue led to comparable declines in both groups, children with CP exhibited poorer baseline performance, potentially resulting in more difficulties in daily activities. This underlines the importance of therapeutic strategies, such as functional power training, that address both baseline deficits and fatigue resilience.

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