SEMMELWEIS EGYETEM

DOKTORI ISKOLA

Ph.D. értekezések

3160.

PULAY MÁRK ÁGOSTON

Transzlációs és klinikai farmakológia

című program

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EFFECTS OF DIFFERENT ADDITIONAL INTERVENTIONS: TRANSLATING RESEARCH FINDINGS INTO REHABILITATION PRACTICES FOR CHILDREN WITH CEREBRAL PALSY

Ph.D. Thesis

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Budapest

2025

"Science means constantly walking a tightrope between blind faith and curiosity; between expertise and creativity; between bias and openness; between experience and epiphany; between ambition and passion; and between arrogance and conviction – in short, between an old today and a new tomorrow.”

Henrich Rohrer

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LIST OF ABBREVIATIONS

1MWT	1-Minute Walk Test
6MWT	6-Minute Walk Test
APF	András Pető Faculty
AOI	Areas of interest
AT	Assistive Technology
CE	Conductive Education
CI	confidence interval
COR	correlation
CP	cerebral palsy
CPQOL	Cerebral Palsy Quality of Life Questioner
FC	fixation count
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure (66 or 88 items)
IT	information technology
ICT	information and communication technology
iOS	iPhone Operating System
MAS	Modified Ashworth Scale
MD	mean difference
1MWT	1-Minute Walk Test
6MWT	6-Minute Walk Test
MVPT-4	Motor-Free Visual Perception Test - fourth edition
N	number – (sample size)
N	Newton (unit of force)
N/A	no data available
NR	not-reported
OR	odds ratio
OT	occupational therapy

PC	personal computer
PBS	Pediatric Balance Scale
PEDI	Pediatric Evaluation of Disability Inventory
PICO	population-intervention-control-outcome
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PT	physiotherapy
RCT	randomized clinical trial
ROM	range of movement
RoB 2	Revised tool for assessing the Risk of Bias
S	spastic
SD	standard deviation
TFD	total fixation duration
TUG	Time Up and Go Test
VC	visit count
VP	visual perceptual
VPI	visual perceptual impairment
WBV	whole-body vibration

1. INTRODUCTION

Cerebral palsy (CP) is a movement disorder characterized by permanent damage to the development of posture and movement caused by non-progressive disturbances that occur during fetal or infant brain development (1). The main symptoms include motor disorders, often accompanied by disturbances in sensation, perception, cognition, communication, and behavior, as well as epilepsy and secondary musculoskeletal problems (2). It is the most common childhood physical disability and affects about 1 in 500 neonates globally with an estimated prevalence of 17 million people worldwide (3), (4). A recent review identified 23 risk factors associated with CP, such as low birth weight (<1500 g), prematurity, an Apgar score of less than 4 at the first minute, grade 3 or 4 intraventricular hemorrhage, preeclampsia, birth asphyxia, preterm premature rupture of membrane (5). Before 5 months of corrected age, the most predictive tools for detecting risk include the Prechtl Qualitative Assessment of General Movements with a sensitivity of 98%, the Hammersmith Infant Neurological Examination with a sensitivity of 90%, and term-age magnetic resonance imaging with a sensitivity of 86%-89% (6).

CP can be classified by functional abilities and by neurological subgroups, which are determined according to the limbs affected (hemiparesis, tetraparesis, or diparesis), clinical signs and symptoms (spasticity, dyskinesia, and hypotonic or mixed), spasticity being the most common (80%) (7), (8).

While there are several classification systems available, the Gross Motor Function Classification System-Expanded & Revised (GMFCS-E&R) is the most frequently used system, consisting of five levels, I (least impairment) to V (most severe impairment). This system provides a standardized classification that assists in prognosis, treatment, and effective communication among clinicians, researchers, parents, and caregivers (9).

CP is a lifelong condition with no cure. Management strategies should adopt a life-course approach, prioritizing increased activity and participation. The severity of impairments in children with cerebral palsy varies widely, from isolated gait and balance disturbances that may only become noticeable in later childhood (GMFCS Level I) to profound cognitive and physical disabilities evident from birth (GMFCS Levels IV or V). Effective management programs must be individualized, addressing the full spectrum of impairments and involving multidisciplinary collaboration among healthcare providers, social care professionals, and families (2), (10). The most common therapeutic interventions are physiotherapy (PT), occupational therapy (OT), conductive education (CE), and the Bobath approach aimed at improving muscle strength, normalizing tone, facilitating normal movement patterns, cognitive and academic functions, and increasing the quality of life (2), (11). There are various other additional therapies that may further enhance the effectiveness of these interventions. We investigated the effectiveness of one such complementary approach: whole-body vibration (WBV).

WBV is a widely utilized technique for muscle training in various clinical settings, particularly for patients with motor disorders such as CP. WBV involves exercising or standing on a vibrating platform that delivers sinusoidal oscillating mechanical vibration platform, which can be applied through the feet to the entire body (12). This modality acts as a potent stimulus for the musculoskeletal system, requiring rapid adjustments in muscle stiffness to accommodate the oscillatory waves. These adjustments are mediated through monosynaptic and polysynaptic afferent pathways, triggering various neuromuscular responses (13).

WBV has also been shown to elicit changes in hormonal profiles and cardiovascular responses, suggesting its potential to improve factors associated with CP (14). Numerous systematic reviews have demonstrated the efficacy of WBV for enhancing musculoskeletal functions in CP patients, including improvements in gross motor function, bone density, spasticity and contracture reduction, balance, and muscle strength (15), (16), (17).

The intensity of WBV is influenced by parameters such as amplitude, frequency, and oscillation magnitude (13), (17). The amplitude, defined as the peak-to-peak displacement (measured in millimeters), is determined by the extent of the oscillatory motion. Frequency, measured in hertz, and acceleration, which reflects the vibration's magnitude, further contribute to its overall intensity. Low-amplitude, low-frequency vibration is particularly effective in enhancing muscle strength, reducing spasticity, and improving musculoskeletal parameters (13), (18), (19). External factors, including body positioning and exposure duration, also play a critical role in determining vibration intensity (20).

A recent study compared two WBV protocols in children with spastic CP: a gradually increasing 7–18 Hz protocol and a static 11 Hz protocol. The 7–18 Hz protocol demonstrated immediate reductions in spasticity, whereas the static 11 Hz protocol was more effective over an eight-week period. Both protocols produced comparable effects on physical performance (21). Another review of 18 studies on WBV therapy protocols for individuals with CP revealed significant variation in program duration (3–24 weeks), session frequency (2–10 per week), and exercise parameters. Static exercises were the most common (67%), with participants primarily adopting a standing position, while some studies included squats or combined static and dynamic exercises. Reporting on key details such as foot, knee, and hip positioning was inconsistent, and only a subset of studies specified conditions like footwear, trunk stabilization, or hand positioning during vibration training (22).

Beyond CP, WBV has demonstrated significant effects in reducing spasticity and improving gait, balance, and motor function in various neurological conditions, including stroke (23), (24).

Cognitive impairments are common among individuals with CP, although their degree and nature can vary significantly. Research indicates that approximately 30–50% of children with CP experience some level of cognitive impairment (25). While the motor impairments associated with CP are well-documented, the cognitive aspects of the condition often receive less attention, despite being equally significant. Cognitive abilities are crucial for communication, academic performance, participation, and social functioning; however, they have historically been underemphasized in both research and clinical practice. Studies on CP predominantly focus on motor impairments, often overlooking the impact of cognitive functions, such as visual perception (VP), on functional abilities (26), (27), (28).

VP is essential for processing visual stimuli, enabling individuals to identify and understand their surroundings. It is one of the many areas often affected in children with CP (29). A study by Schmetz et al. (30) found that children with CP aged 5–18 years, experience persistent deficits in VP, also referred to as visual perceptual impairment (VPI), compared to typically developing peers. VP comprises several specific domains, including visual discrimination, visual form constancy, and figure-ground perception, all of which contribute to functional tasks. Due to the varied brain lesion patterns characteristic of CP, there is no universally accepted prevalence rate for VPI in children with CP (31). In children with CP, deficits in visual perception can significantly impact academic performance, particularly in reading and learning, as well as activities of daily living, such as dressing (29), (32), (33). The relationship between motor-visual and visual-motor development is well-documented, as CP often leads to impairments in both motor skills and perceptual and cognitive visual abilities (29), (34), (35).

Recent advances in information and communication technology (ICT) have brought significant changes to traditional approaches in special education and early intervention (36), (37). These findings lead us to create an application that supports VP skills development. This project emerged from the daily practice of conductive education as a demand-driven initiative, addressing the lack of software tools for early intervention and the development of sub-skills such as visual-auditory perceptual abilities.

Special attention was given to ensuring the application could run on a variety of information technology (IT) assistive technologies (AT), including eye-tracking devices, switch technology, and specialized mouse interfaces. These adaptations were critical to meeting the needs of the primary target group: children with severe physical disabilities. By incorporating these technologies, the application aims to bridge gaps in early intervention tools and enhance opportunities for children with CP to develop essential perceptual and cognitive skills.

As a conductor-teacher, my focus is on fostering the holistic development of individuals with neurological disorders, such as CP. Conductive education is a holistic approach to improving motor, cognitive, self-care, social skills, and overall quality of life. However, the complexity of these conditions often necessitates the integration of additional interventions to address specific impairments more effectively. Exploring and incorporating evidence-based additional therapies, such as WBV or AT-supported applications, can significantly enhance daily practice. Understanding the benefits and limitations of these therapies is crucial for developing tailored and effective rehabilitation strategies.

2. OBJECTIVES

2.1. Study I. – The Effect of Additional Whole-Body Vibration on Musculoskeletal System in Children with Cerebral Palsy

The primary objective of this study is to evaluate the effects of WBV therapy as an additional intervention to conventional physiotherapy (PT) on the musculoskeletal system in children with CP. Specific goals:

- Assessing the impact of WBV on key outcomes such as muscle strength, spasticity, balance, and gait-related functions (e.g., walking speed and step length).
- Investigating differences in WBV effects across varying protocols, including frequency, amplitude, exercise positions, and session durations.
- Exploring subgroup differences based on CP severity levels (GMFCS I–V) to identify potential variations in treatment efficacy.
- Identifying the short- and long-term effects of WBV therapy, including its ability to normalize muscle tone and improve gross motor function.

2.2. Study II. – Developing Visual Perceptual Skills with Assistive Technology Supported Application for Children with Cerebral Palsy

This study aimed to design and evaluate the effectiveness of an educational application tailored to develop visual perceptual skills in children with CP. Specific goals:

- Assessing the application's impact on visual perceptual skills using the Motor-Free Visual Perception Test (MVPT-4).
- Analyzing changes in gaze patterns and visual attention using screen-based eye-tracking technology.
- Comparing the intervention group's outcomes with a control group to determine the application's effectiveness in enhancing visual perceptual sub-skills such as visual discrimination, spatial awareness, and figure-ground perception.
- Highlighting the potential relationship between physical abilities and visual perceptual skills in children with CP.

3. METHODS

This section outlines the methodologies employed in the two studies presented in this thesis. The first study focuses on the effects of whole-body vibration (WBV) therapy in children with cerebral palsy (CP), and the second study investigates the development of visual perceptual skills through the use of assistive technology-supported applications. Each study involves children living with CP, and the methods are addressed separately, with detailed descriptions of their respective designs, procedures, and analyses.

3.1. Study I. The Effect of Additional Whole-Body Vibration on Musculoskeletal System in Children with Cerebral Palsy

This systematic review and meta-analysis adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (38). The PRISMA is a standardized framework for systematic reviews evaluating health interventions and provides flexibility to accommodate various study designs (39). The review protocol was registered on PROSPERO (CRD42021284999).

3.1.1. Eligibility criteria

The review included randomized controlled trials (RCTs) that assessed the effects of WBV on musculoskeletal outcomes in children with CP, regardless of subtype or GMFCS level. The primary outcomes of interest included muscle strength, spasticity, gross motor function, bone density, and walking skills, such as speed, walking distance, and balance. Only studies that measured these outcomes in a comparable and quantitative manner were included.

The Population, Intervention, Comparator, and Outcome (PICO) framework (40) guided the search strategy. The population included children diagnosed with CP, with one group receiving WBV therapy with conventional physiotherapy (PT) and the comparator group receiving either a placebo, sham, or simulated intervention alongside conventional PT. The primary outcomes were changes in musculoskeletal functions, such as mobility, balance, muscle strength, spasticity, bone density, gross motor function, gait speed, walking distance, and overall motor performance.

3.1.2. Study selection and data collection

Two reviewers independently conducted the study selection process using reference management software (Endnote X9 3.3, Clarivate Analytics). Duplicate records were removed both automatically and manually. The remaining records were screened by title, abstract, and full text according to predetermined criteria outlined in the data selection and extraction protocol. Discrepancies between the two reviewers were resolved through consensus. Agreement rates were calculated at each stage using the Cohen's kappa coefficient to ensure reliability.

Studies published before November 1, 2022, were retrieved from the following databases: MEDLINE (via PubMed), Embase, Cochrane Central Register of Controlled Trials, Scopus, and Web of Science. The search strategy employed the following keywords: ("cerebral palsy" OR paraplegia OR diplegia OR CP OR hemiparesis OR hemiplegia OR tetraplegia) AND ("whole body vibration" OR "whole-body vibration" OR WBV OR "vibration therapy" OR vibration). No restrictions or filters were applied.

Data extraction was independently performed by two reviewers (M.Á.P. and Z.N.) using a standardized data collection sheet (Excel 2019, Microsoft Corp). The extracted data included demographic details (age, sex), type and severity of CP (if reported), patient numbers, and mean or median values of relevant outcomes. Information on the WBV intervention settings and control group physiotherapy was also documented. The setting of the WBV intervention and control group conventional PT.

The following data were collected from each eligible article:

- Article-specific details: First author, publication year, DOI, language, study design, study duration, and original data source.
- Participant-related details: Demographics, subject characteristics (age, sex, applied treatments), and any reported subgroups.
- Outcome-related details: Comprehensive data on all outcomes of interest.
- For studies reporting on the same population, multiple reports were cross-referenced and linked to ensure accuracy and consistency.

3.1.3. Quality assessment

The risk of bias assessment was conducted independently by two reviewers using the revised Cochrane Risk-of-Bias Tool for Randomized Trials (RoB 2) (41). The reviewers evaluated each selected article across five domains: the randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. To ensure rigor, specific inclusion criteria were established for the evaluators: expertise in the field, trained in risk of bias assessment, and pilot testing. Based on the evaluations, studies were categorized as having a low risk of bias, some concerns, or a high risk of bias. Any disagreements between the reviewers were resolved through consensus discussions.

3.1.4. Data synthesis and analysis

The statistical analyses were conducted using the 'meta' package in R statistical software (version 4.1.2), following the recommendations of Harrer et al. (42).

The efficiency of WBV was assessed by analyzing the mean and standard deviation of changes in various outcome measures before and after treatment in both the WBV intervention group and the control group, albeit with certain limitations outlined in the Limitations section. Subsequently, a random effect meta-analysis was employed to evaluate the differences in mean changes. The classical inverse variance method with the restricted maximum likelihood estimator was utilized for this analysis. As only a few studies contributed to the meta-analysis, the Hartung-Knapp adjustment was applied. Besides the prediction interval, heterogeneity was assessed by calculating the I^2 measure and its confidence interval and performing the Cochrane Q test. I^2 values of 25%, 50%, and 75% were considered low, moderate, and high heterogeneity, respectively. It should be noted that a positive pooled value indicates that the change in the treatment group was larger.

Whenever possible, correlations between pre- and post-treatment outcome values were calculated using raw data obtained from study authors or published summary statistics. The average of these correlations was used to estimate the standard deviation of change when missing data occurred. Subgroup analyses were planned based on CP subtypes and GMFCS categories, though these were contingent on data availability.

3.2. Study II. Developing Visual Perceptual Skills with Assistive Technology Supported Application for Children with Cerebral Palsy

A matched-pair randomized controlled trial was conducted to investigate the effectiveness of specialized educational software and learning games designed to enhance various sub-skills in preschool and elementary school children with typical and atypical development (e.g., CP).

3.2.1. Intervention enrollment and technical features

The intervention period lasted for a full school year (9 months). During this time, participants in the intervention group were allowed to use the applications for 15 minutes at least three times a week. While some participants used tablets, others utilized an eye-tracking device to interact with the applications. This schedule was developed in collaboration with the conductors in the department to ensure alignment with their daily conductive education program. The control group did not use the applications; instead, they participated exclusively in their regular conductive education program.

The applications run on PCs (web-based) and tablets (iOS, Android). The software collects statistical data about users, enabling the observation of positive changes and identification of problematic areas. It provides real-time feedback to caregivers regarding the children's performance. In addition to its functional software design, usability, and ergonomic features were incorporated to evaluate the software's positive effects on cognition, particularly on visual perceptual skills. Another key feature is gamification, which aims to capture and maintain the user's attention and motivation. The user interface is tailored to meet children's needs, featuring a playful and colorful design, varying levels of difficulty, and reward collection opportunities. The intervention targeted specific developmental areas that were chosen based on their relevance to the cognitive, perceptual, and motor skill development of children with typical and atypical development. The following areas were assessed and addressed during the use of the educational software and learning games:

- Visual perception skills: such as visual discrimination, spatial relationships, visual memory, figure-ground, visual closure, perception and recognition of colors and shapes,

- Auditory perception skills: such as auditory closure, auditory conceptualizing, auditory discrimination, auditory memory, and auditory sequential memory,
- Basic mathematical operations (summations, subtractions), and problem-solving skills,
- On tablet: eye-hand coordination, fine manipulation, hand dominance,
- Rule consciousness,
- Decision-making skills,
- Self-awareness.

These areas were systematically addressed through the interactive features of the software, incorporating gamification and adaptive levels of difficulty to meet individual needs.

3.2.2 Participants characteristics

The participants, aged between 4 and 8 years (mean 7.27 ± 1.53), were recruited from the Semmelweis University, András Pető Faculty Kindergarten and Elementary School.

The total sample size was N=18, with equal distribution between the intervention group (N=9) and the control group (N=9).

Participants were matched in pairs based on their age and diagnosis to ensure comparability between groups.

We also conducted the baseline measurement (MVPT-4 test and eye-tracking) with typically developing children (N=12) to analyze and compare this population's visual perceptual skills and gaze patterns (**Table 1**.).

The exclusion criteria were:

- Children with uncorrectable visual or hearing impairments that would prevent them from using the application.
- Participants unable to comprehend or respond to the MVPT-4 tasks.
- Children with significant behavioral challenges that hinder participation.
- Children with unstable medical conditions or undergoing acute medical treatment that may interfere with participation.
- Cases where informed consent is not provided by parents or legal guardians.

Table 1. Patient characteristics (43).

Group	N	Age (Mean ±SD	CP Diagnosis
Total	18	7.27 ± 1.53	Tetraparesis: N=6, Athetosis: N=2, Ataxia: N=2, Hemiplegia: N=2, Slightly affected: N=6
Intervention	9	7.27±1.37	Matched in pairs based on age and diagnosis
Control	9	7.25±1.76	Matched in pairs based on age and diagnosis
Reference	12	7.67±2.39	typically developing children

3.2.3 Research Tools

3.2.3.1. Motor-Free Visual Perception Test – 4 (MVPT-4)

The MVPT-4 is the latest revision of the Motor-Free Visual Perception Test (MVPT), originally developed in 1972. Subsequent revisions include the MVPT-Revised (MVPT-R) in 1996, the MVPT-3 in 2003, and the MVPT-4 in 2015. This version was designed to assess the visual-perceptual abilities of individuals aged 4 through 80+ years using a series of visual-perceptual tasks that do not require a motor response (44), (45). The test evaluates five visual-perceptual abilities: visual discrimination, spatial relationships, visual memory, figure-ground, and visual closure. However, the scores for these subtests are not reported individually; instead, they are combined into a single overall visual-perceptual ability standard score. Colarusso and Hammill, the test's authors, describe the MVPT-4 as a quick, accurate, reliable, and valid tool for assessing overall visual-perceptual ability (46). The stimuli consist of black-and-white line drawings and designs, presented in a multiple-choice format. The test's motor-free design allows the assessment of VP skills without requiring a motor response, making it especially valuable for those with severe forms of CP where motor manipulation is impaired.

3.2.3.2. Eye-Tracking

The Tobii Pro X3 is a screen-based eye tracker that captures gaze data at 120 Hz, providing an unobtrusive and direct method for researchers, eliminating the need to rely exclusively on self-reported measures (47), (48). Eye-gaze fixations and saccades can be analyzed to gain insights into participants' intentions and cognitive strategies within the context of specific tasks (49), (50).

Data collected from the eye tracker records the position of the eyes in relation to the scene viewed over time. Two essential features of this data are fixations, defined as a steady gaze on a particular location for a specific duration, and saccades, which are quick eye movements between locations (49), (51), (52). Eye-tracking has been used to detect subtle differences between clinical and typically developing populations across different age groups. Research has shown its potential to identify attention patterns linked to cognitive processes or conditions such as affective disorders, addiction, and premature birth (53), (54).

For this study, we digitalized the MVPT-4 test sheets to enable computerized test completion and facilitate the capture of participants' gaze patterns. We aimed to explore the suitability of eye-movement recordings for identifying gaze patterns that provide insights into participants' cognitive processing during the MVPT-4 test. Specifically, we examined whether eye movement patterns could distinguish between atypically developing children exposed to the application and those who were not over the course of the intervention period (one school year). This included analyzing areas where typically developing children showed consistent fixations while processing tasks, compared to areas where atypically developing children exhibited reduced or absent fixations.

3.2.4. Research Questions

Research Questions Concerning the MVPT-4:

- What are the differences in MVPT-4 scores between typically developing and atypically developing children?
- How do MVPT-4 scores differ between the intervention group and the control group after the intervention period?

- Are there differences in MVPT-4 scores among children with different CP diagnoses?

Research Questions Concerning Eye-Tracking Data:

- What are the differences in gaze patterns between typically developing and atypically developing children?
- How do gaze patterns and levels of visual attention differ between baseline and re-test measurements?

3.2.5. Data Analysis

For the data analysis, IBM SPSS 26 software was used. Due to the non-normal distribution of the data and the small sample size, the Wilcoxon signed-rank test (Wilcoxon matched pairs test) was applied to compare baseline and re-test values within each group (test and control). This test examines the difference between paired samples and is suitable when two continuous measurements are made on the same group. It evaluates how much the median of the differences deviates from zero. Research on small sample sizes suggests that the Wilcoxon test provides increased statistical power compared to the t-test when the assumption of normality is violated (55). The Mann-Whitney U test was used to compare the MVPT-4 test results between the two independent groups (intervention and control). This test is appropriate for analyzing differences between two independent groups when the dependent variable is ordinal or continuous but not normally distributed (56), (57).

The eye-tracking software enabled the selection of specific Areas of Interest (AOI). For this study, we identified and collected the AOI-s corresponding to the correct figures (answers) on the digitalized MVPT-4 test sheets. Three variables were analyzed: total fixation duration (TFD), fixation count (FC), and visit count (VC). To ensure the robustness of the analysis, we conducted distribution tests for each variable. For comparing gaze patterns between the "typically" and "atypically" developing groups, we applied a t-test for normally distributed data and a Mann-Whitney U test for non-parametric data. The baseline and post-intervention values for the intervention and control groups were compared using repeated measures ANOVA for variables with a normal distribution. For non-parametric data, Mann-Whitney U tests were used to evaluate within-group changes between baseline and post-intervention values, as well as the differences between these values. The Friedman test was deemed unsuitable due to missing values.

3.2.6. Ethical Consideration

Parents of the participants were thoroughly informed about the details of the research and the data management procedures. Written informed consent was obtained from all parents prior to their children's participation. The study did not involve any invasive procedures or the collection of sensitive data. All collected data were anonymized and handled in compliance with the applicable GDPR regulations to ensure the privacy and confidentiality of the participants.

4. RESULTS

This section presents the findings of the two studies included in this thesis. The results are organized into separate subsections for each study, ensuring clarity and consistency in presenting the key findings.

4.1. Study I. The Effect of Additional Whole-Body Vibration on Musculoskeletal System in Children with Cerebral Palsy

4.1.1. Search and selection, characteristics of the included studies

Our systematic search provided a total of 5,984 potentially relevant records across the databases. After removing 1,890 duplicates, 4094 titles and abstracts were screened, of which 3,976 were excluded for not meeting the eligibility criteria. Out of the remaining 118 studies, 102 were excluded after full-text selection. This was primarily due to the studies not being RCTs, employing inappropriate study designs (e.g., differing comparisons among observed groups), or involving overlapping patient populations. Based on the inclusion and exclusion criteria, 16 articles, encompassing 414 patients, were included in the final analysis. Of these, 16 studies were deemed eligible for inclusion in the systematic review, and 12 were integrated into the meta-analyses. The remaining four studies were excluded because they either employed specialized or unusual measurement techniques or did not report statistical results appropriately. The PRISMA flowchart illustrating this process is displayed in **Figure 1**.

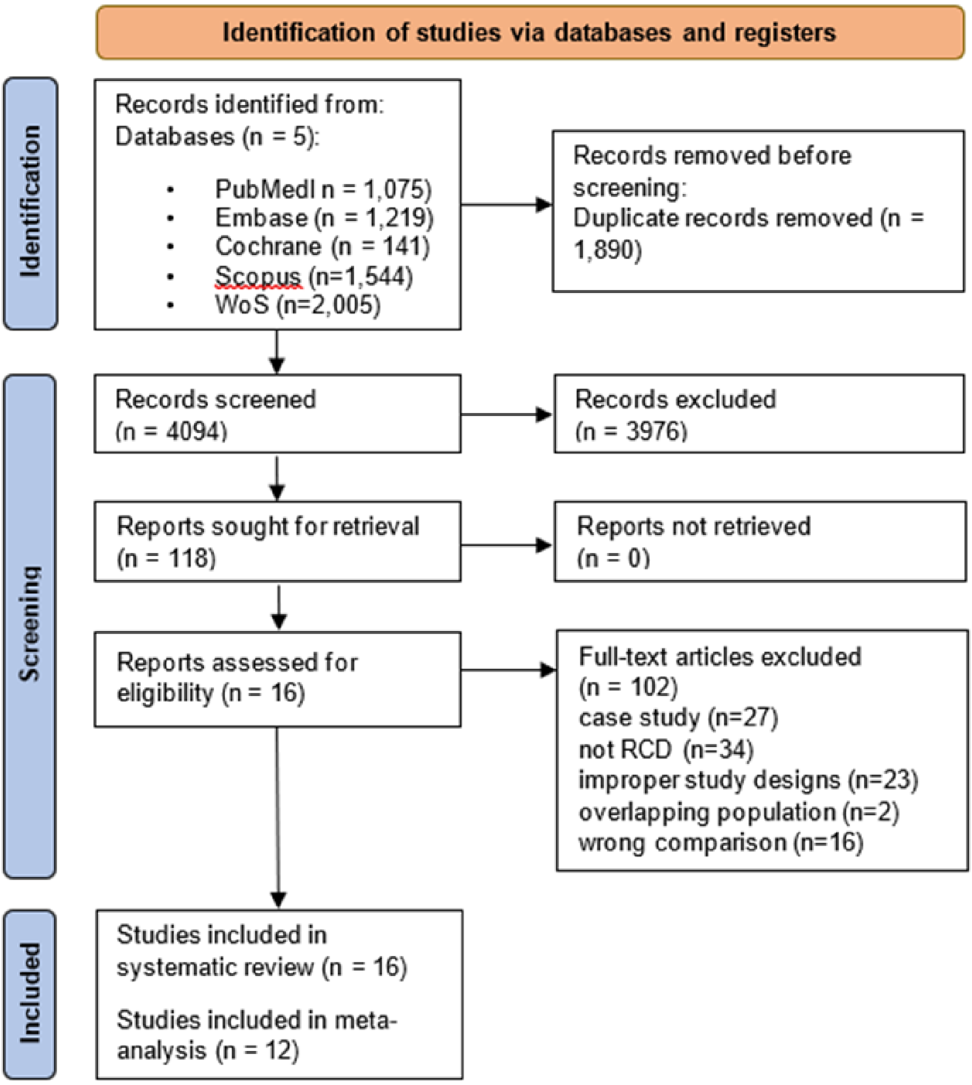

Figure 1. PRISMA Flow Diagram of the screening and selection process (58).

Comprehensive details regarding the articles included in the systematic review are summarized in **Table 2**, which compiles all relevant study characteristics. The 16 reports included in this systematic review were published between 2010 and 2022.

The mean age of participants ranged from 19 months to 11.82 years. Regarding the patients' characteristics, some studies exclusively reported data on the Gross Motor Function Classification System (GMFCS) levels of the subjects, ranging from levels I to IV. Other studies specified the type of CP, such as hemiplegia, diplegia, or tetraplegia. Additionally, certain studies provided comprehensive information by reporting both GMFCS levels and CP types concurrently. For detailed data, refer to **Table 2.**

The studies employed two primary types of randomized study designs:

- Randomized clinical trials: Subjects were divided into two groups. The intervention group received WBV combined with conventional physiotherapy (PT), while the control group received a placebo, sham, or simulated intervention alongside conventional PT, or conventional PT alone as a control.
- Crossover study designs: subjects were randomly allocated to either the AB or BA sequence (A treatment / B intervention group).

Conventional PT used in these studies for children with CP has been shown to improve muscle strength, local muscular endurance, joint range of motion, and incorporates neurodevelopmental techniques, proprioceptive training, and balance training.

The outcomes measured in the selected studies cover a wide spectrum, most of them related to the musculoskeletal system.

- Gross motor function: assessed primarily with GMFM-66 or GMFM-88.
- Spasticity: measured using the Modified Ashworth Scale (MAS).
- Walking ability: evaluated with tests such as 1-Minute Walk Test (1MWT), 6-Minute Walk Test (6MWT), and Time Up and Go Test (TUG).

All outcome measurement methods are displayed in **Table 2**.

Regarding biomechanical parameters related to WBV exercises and devices, there was considerable variation across studies (see **Table 2.**). Most studies utilized either side-alternating or vertical platforms with frequencies ranging from 5 to 40 Hz and exercise durations from 30 seconds to 10 minutes. The most frequently employed intensity regimen consisted of 3 sets of 3 minutes each, with 3 minutes of rest between sets. In terms of body positioning, the majority of studies incorporated muscle-strengthening exercises targeting the lower limbs while utilizing WBV.

Table 2. Main Characteristics of the articles included in the systematic review (58).

	Patient characteristic				Groups		Outcome	Intervention setup
Study	**Type of CP**	**GFFCS level**	**N**	**Age**	**Treatment**	**Control**	**Outcome measures**	**Frequency (x per Week) Length (Week) Intensity**
Ahmadizadeh et al. 2019 (59)	S. Hemiplegia (N=9) S. Diplegia (N=10) Tetraplegia (N=1)	I, II, III	20	7.5 years SD±2.23	Conventional Therapy + WBV	Conventional Therapy	Goniometry, spasticity, 6MWT, ROM	2x3 min 3 times/week 6 weeks 20-24 Hz
Ali MS and Abd El-aziz HG 2020 (19)	S. Diplegia	I, II, III, IV	30	5.23 years SD±0.96	Conventional Therapy + WBV	Conventional Therapy	GMFM-88 sitting domain, abdominal muscle thickness-ultrasonography	2x5 min 3 times/week 12 weeks 30 Hz
Aslam and Baig 2022 (60)	NR	II, III	38	9.36 years SD±1.26	Conventional Therapy + WBV	Conventional Therapy	MAS spasticity, manual muscle testing, pediatric balance scale, CPQOL	1x3 min 3 times/week 4 weeks 40 Hz
Cheng et al. 2015 (61)	S. Diplegia (N = 11) S. Quadriplegia (N = 5)	NR	16	9.2 years SD±2.1	Conventional Therapy + WBV	Conventional Therapy	AROM, PROM, RI, MAS spasticity, TUG, 6MWT	1x10 min 3 times/week 8 weeks 20 Hz
Dudoniene et al. 2017 (62)	S. Diplegia	NR	20	8.60 years SD±0.96	Conventional Therapy + WBV	Conventional Therapy	Spasticity, range of motion, GMFM-88	5-10 min 5 times/week 3 weeks 15 Hz

El-Shamy 2014 (12)	S. Diplegia	I, II	30	9.79 years SD±1.13	Conventional Therapy + WBV	Conventional Therapy	Knee extensor strength, stability index	3x3 min 5 times/week 12 weeks Vibraflex Home Edition II. 12-18 Hz
Hegazy et al. 2021 (63)	S. Hemiplegia	I, II	40	6.95 years SD±1.46	Conventional Therapy + WBV	Conventional Therapy	Quadriceps, hamstring muscle strength, endurance, 6MWT and power	3x3 min 3 times/week 8 weeks 10-25 Hz
Ibrahim et al. 2014 (64)	S. Diplegia	NR	30	9.93 years SD±1.41	Conventional Therapy + WBV	Conventional Therapy	Knee extensor strength, walking Speed, walking balance, gross motor function	3x3 min 3 times/week 12 Week 12-18 Hz Power Plate
Lee and Chon 2013 (65)	S. Diplegia S. Hemiplegia	NR	30	9.83 years SD±2.39	Conventional Therapy + WBV	Conventional Therapy	gait analyses and ultrasonographic imaging of the leg muscles	6x3 min 3 times/week 8 weeks 5-25 Hz
Myung-Sook 2015 (66)	S. Diplegia (N=14) S. Hemiplegia (N=10)	I, II, III	24	9.52 years SD±2.38	Conventional Therapy + WBV	Conventional Therapy	Gait analyses, TUG test, Functional Independence Measure for Children (WeeFIM)	3x3 min 2 times/week 3 weeks 20-24 Hz Galileo
Ruck et al. 2010 (67)	NR	II, III, IV	20	6.2 to 12.3 years	Conventional Therapy + WBV	Conventional Therapy	Walking ability, bone densitometry, gross motor function	3x3 min 5 times/week 24 weeks 12-18 Hz Galileo
Stark et al. 2016 (68)	NR	II, III, IV	24	19 months SD±3.1	Conventional Therapy + WBV	Conventional Therapy	GMFM-66, PEDI,	3x3 min 10 times/week 14 weeks

								12-22 Hz
Tekin and Kavlak 2021 (69)	S. Hemiplegia	NR	22	11.82 years SD±3.55	Conventional Therapy + WBV	Conventional Therapy	Gait Analysis, standing, walking, balance, spasticity, gross motor function	1x15 min 3 times/week 8 weeks 15 Hz Compex-Winplate
Tupimai et al. 2016 (70)	NR:	I, II, III	12	10.6 years SD±2.4	Conventional Therapy + WBV	Conventional Therapy	MAS spasticity, PEDI, muscle strength	10x1 min 5 times/week 6 weeks 20 Hz
Unger et al. 2012 (71)	S. Diplegia S. Hemiplegia	I, II, III	27	6-13 years	Conventional Therapy + WBV	Conventional Therapy	1MWT, 2D-posturography, ultrasound imaging and sit-ups in one minute	30-40 sec 5 times/ week 4 weeks 35-40 Hz
Wren et al. 2010 (72)	S. Diplegia (N=18) S. Hemiplegia (N=4) S. Tetraplegia (N=9)	I, II, III, IV	31	9,4 years SD±1.4	Conventional Therapy + WBV	Conventional Therapy	Bone density, plantar flexor strength	1x10 min 10min/day 6 months (at home) 30 Hz

Abbreviations: NR, not-reported; S, Spastic; WBV, Whole Body Vibration; GMFCS, Gross Motor Function Classification; GMFM (66 or 88), Gross Motor Function Measure; PEDI, Pediatric Evaluation of Disability Inventory; MAS, Modified Ashworth Scale; 1MWT, 1-Minute Walk Test; 6MWT, 6-Minute Walk Test; TUG, Time Up and Go Test; (P/A) ROM, (Passive/Active) Range of Movement; CPQOL, Cerebral Palsy Quality of Life Questioner

4.1.2. Therapeutic effects

4.1.2.1. Gross motor function

The Gross Motor Function Measure (GMFM) measures the performance of the child in five dimensions, and each dimension can be measured separately or together (73). However, statistical analysis was feasible only for domains D (standing) and E (gait activities) due to limited overlap in the domains assessed by the individual studies, as depicted in **Figure 2**. While most studies reported positive changes in gross motor functions, the pooled effect size was ultimately nonsignificant. For domain D, the mean difference (MD) was 2.80 (95% CI: -4.56, 10.15), and for domain E, the MD was 5.74 (95% CI: -8.38, 19.85). Importantly, the study conducted by Tekin et al. (69) demonstrated minimal change following the intervention. Nonetheless, it is noteworthy that the baseline GMFMD value of the included patients closely resembles that of typically developing children.

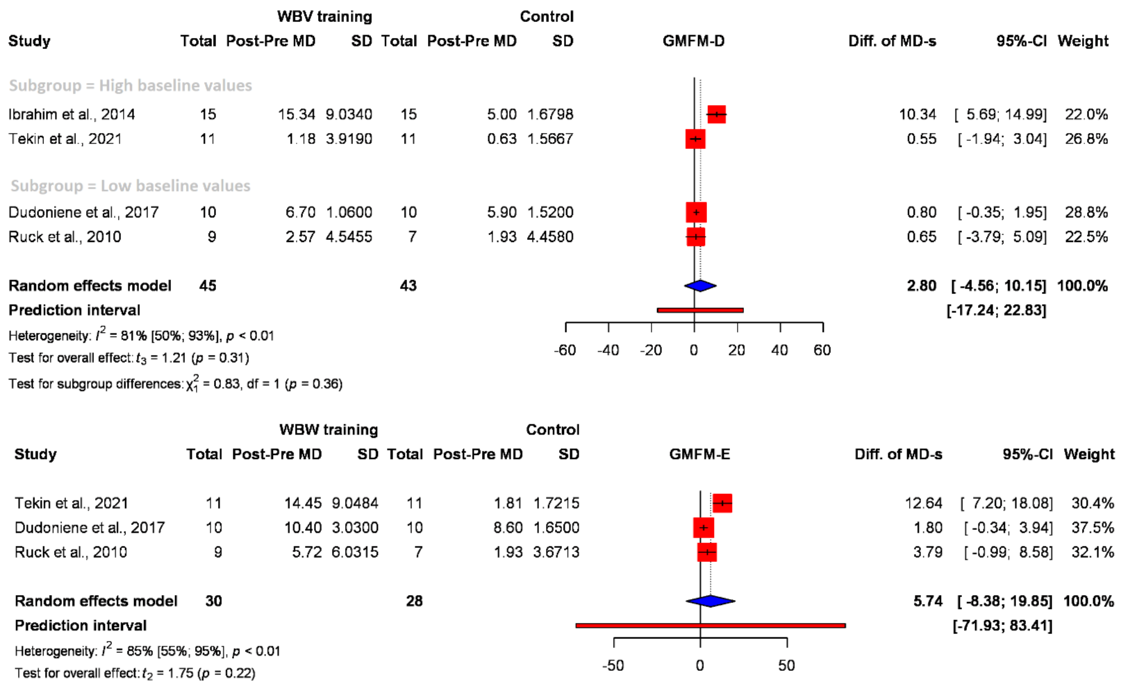

Figure 2. Forest plots displaying the efficacy of whole-body vibration (WBV) on standing (GMFM D- domain), and walking, running, and jumping (E-domain) between intervention and control groups (58).

4.1.2.2. Muscle strength

Four studies (12) (62) (63) (72) assessed muscle strength as an outcome, three of them measuring knee extensor strength using a dynamometer, reported in Newtons (N). The difference between WBV training and the control group was statistically nonsignificant (MD = 8.77, 95% CI: -12.06, 29.59); however, a positive pooled MD in changes between the treatment groups was observed (**Figure 3**).

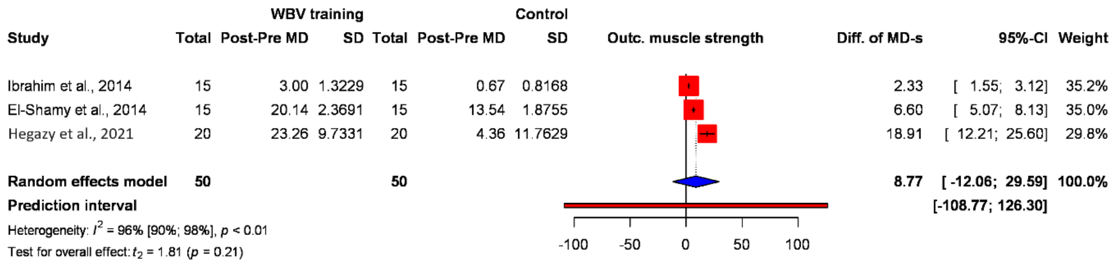

Figure 3. Forest plot with the pooled value of the difference of the MD's showing the effect of whole-body vibration (WBV) on muscle strength in intervention and control groups (58).

4.1.2.3. Walking performance

The effects of WBV treatment on walking skills were assessed not only with the GMFM E domain but also through various measures, including walking speed, step length, 6-Minute Walk Test (6MWT) (74), and Time Up and Go Test (TUG) (75). **Figure 4.** illustrates two walking-related outcomes: walking speed and step length. Significant changes were observed in these two strongly related outcomes:

- Walking speed (cm/s): (diff. of MD 10.03) (95% CI: 4.22; 15.1583) (p = 0.02)
- Step length (cm): (diff. of MD 7.19) (95% CI: -0.15; 14.53) (p = 0.05).

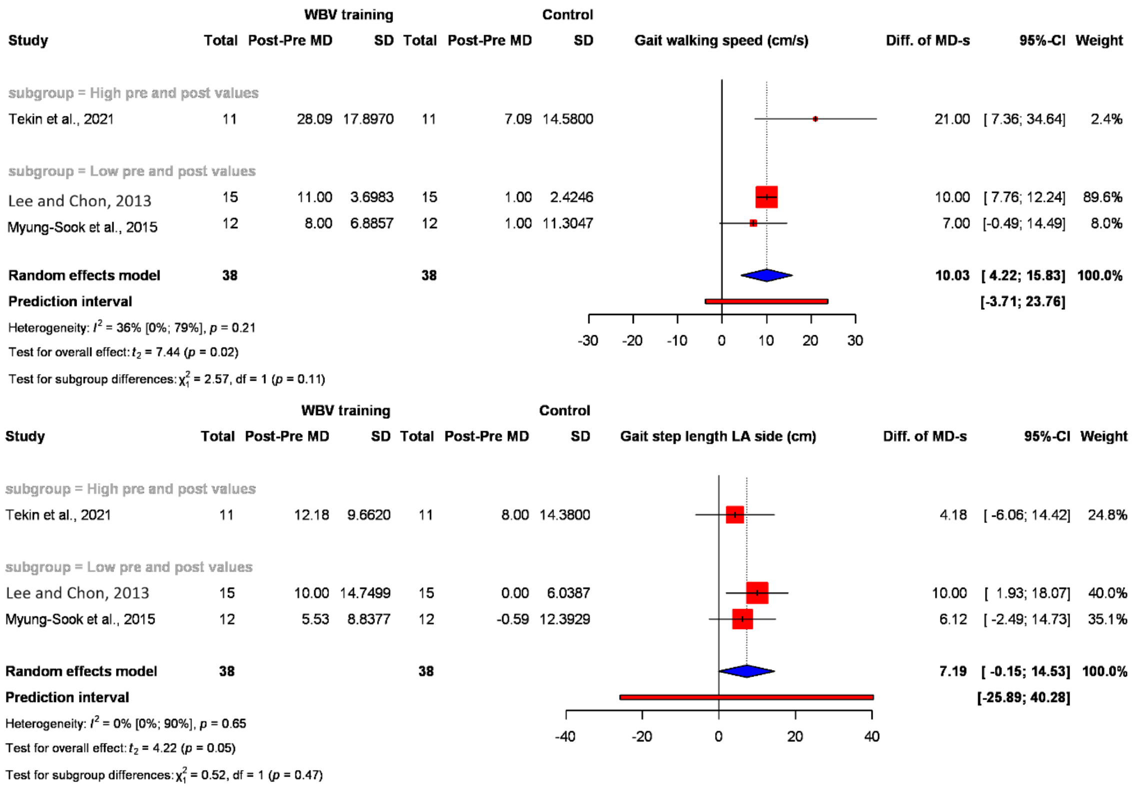

Figure 4. Forest plot with the pooled value of the difference of MD's showing the walking-related outcomes (walking speed and step length) in the intervention and control groups (58).

The two other walking-related outcomes were nonsignificant:

- 6MWT (meter/6min.): (diff. of MD 59.55) (95% CI: -164.26; 283.36) as shown in **Figure 5**.
- TUG (test compl. in sec.): (diff. of MD -2.88) (95% CI: -10.37; 4.62) displayed in **Figure 6.**

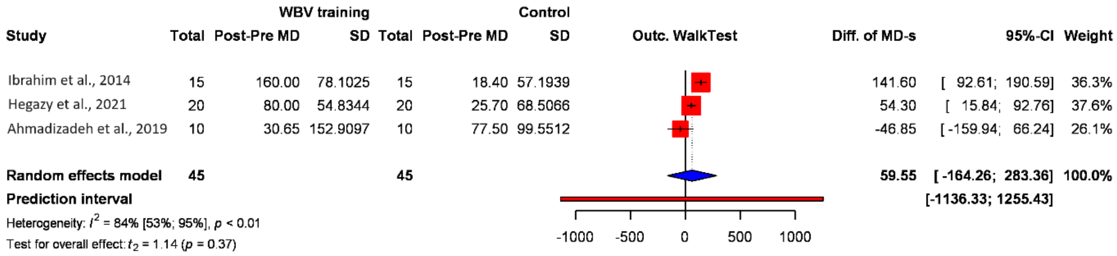

Figure 5. Forest plot with pooled value of the difference of the mean differences showing one of the walking ability-related outcomes, 6 Minute Walk Test in the intervention and control group (58).

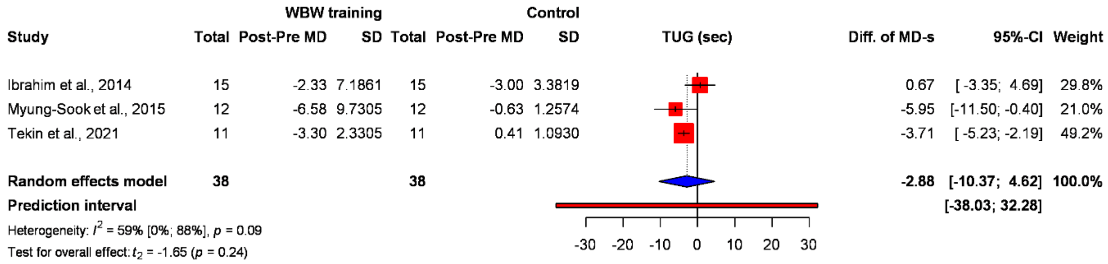

Figure 6. Forest plot with pooled value of the difference of the mean differences showing one of the walking-related outcomes, TUG, Time Up and Go Test in the intervention and control group (58).

4.1.2.4. Spasticity

Five studies (59), (61), (62), (69), (70) assessed spasticity using the Modified Ashworth Scale (MAS), a clinical tool commonly used to measure muscle spasticity in individuals with neurological conditions (76). For statistical evaluation, MAS scores were assigned numeric values ranging from 0 to 5 (70).

Of the five studies, three were included in the statistical analysis due to missing data. While all studies reported increased muscle tone in the lower extremities; however, the pooled effect size did not reach statistical significance (diff. of MD -0.79) (95% CI: -2.83; 1.25), as illustrated in **Figure 7.**

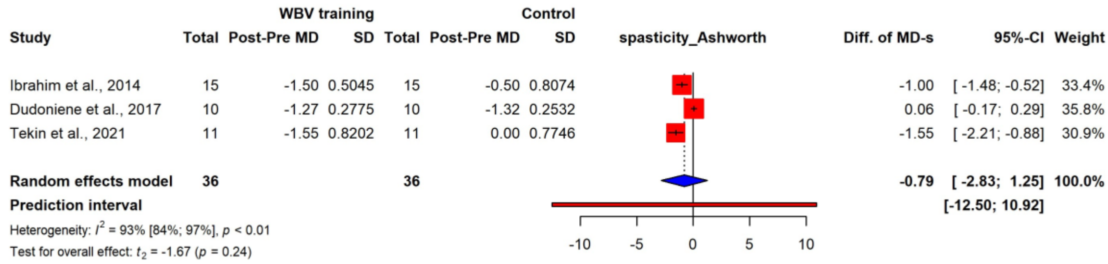

Figure 7. Forest plot with pooled value of the difference of the MD's representing the change of spasticity (measured with Ashworth scale) between intervention and control groups (58).

4.1.2.5. Overall stability

Four studies (12), (59), (70), (77) assessed the effect of WBV on overall stability or balance. However, the use of various measurement methods across studies rendered statistical analysis infeasible. Fatih Tekin and Kavlak (69) evaluated participants' balance skills using a SportKAT 550™ portable computerized kinesthetic balance device. Their findings indicated that balance scores in the WBV group improved significantly after treatment compared to pretreatment levels ($p = 0.03$), and these improvements were maintained after 12 weeks ($p = 0.184$). Myung-Sook Ko et al. (77) reported that static postural balance improved following WBV interventions; however, the changes were not statistically significant in either the WBV or control group. El-Shamy SM (12) observed that the overall stability index post-treatment was 2.75 for the control group and 2.2 for the experimental group. Although stability index values improved in both groups, the experimental group demonstrated a significantly greater increase compared to the control group ($p < 0.001$). Aslam and Baig (60) used the Pediatric Balance Scale (PBS) (78) to evaluate balance and found statistically significant improvements ($p < 0.001$) in the WBV group compared to the control group.

4.1.3. Secondary Outcomes

4.1.3.1. Muscle thickness

Two studies investigated the positive effects of WBV on muscle thickness. Byoung-Kwon Lee and Seung-Chul Chon (65) conducted an RCT involving 30 patients with CP. Their findings indicated that the experimental group exhibited significantly greater increases in tibialis anterior muscle thickness ($p = 0.001$; 0.48 ± 0.08 mm to 0.63 ± 0.10 mm) and soleus muscle thickness ($p = 0.001$; 0.45 ± 0.04 mm to 0.63 ± 0.12 mm) compared to the control group. However, no significant effect was observed on gastrocnemius muscle thickness ($p = 0.645$) (65). Another study (19) reported significant post-treatment improvements in muscle thickness parameters in favor of the experimental group ($p < 0.05$). These included increases in the thickness of the four abdominal muscles compared to the control group:

- External oblique: F=38.783, $p<0.05$
- Internal oblique: F = 99.547, $p<0.05$
- Transverse abdominis: F=111.557, $p<0.05$
- Rectus abdominis: F=129.940, $p<0.05$

4.1.3.2. Bone density

Since the last systematic review on this topic (15), none of the new RCTs investigated the effect of WBV on bone density. They earlier reported a significant improvement of 1.32 (95% CI: 0.28, 2.36, N = 47) in bone density for participants in the WBV group compared to the control group. However, a nonsignificant improvement of 0.41 in lumbar spine bone density was observed (95% CI: -0.42, 1.25, N = 77) (15).

4.1.4. Risk of bias

The included studies were assessed for key domains of bias, including the randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. The risk of bias (RoB) evaluations for each outcome are summarized in **Figure 8**. Most biases were assessed as having "some concern," primarily due to issues related to the selection of the reported result. However, the overall judgments predominantly indicated a "low risk" of bias.

Study	D1	D2	D3	D4	D5	Overall
Ahmadizadeh et al. [26]	+	+	+	+	+	+
Ali MS and Abd El-aziz HG [15]	+	+	+	+	!	+
Aslam and Baig [27]	+	+	+	+	!	+
Cheng et al. [28]	!	+	+	+	!	+
Dudoniene et al. [29]	+	+	+	+	+	+
El-Shamy [8]	+	+	+	+	+	+
Hegazy et al. [30]	+	+	+	+	+	+
Ibrahim et al. [31]	+	+	+	+	+	+
Lee and Chon [7]	+	+	+	+	+	+
Myung-Sook et al. [32]	+	+	+	+	+	+
Ruck et al. [33]	+	+	+	+	+	+
Stark et al. [34]	+	+	+	+	!	+
Tekin and Kavlak [35]	+	+	+	+	+	+
Tupimai et al. [36]	+	+	+	+	!	+
Unger et al. [37]	+	+	+	+	+	+
Wren et al. [38]	+	+	+	+	!	+

Figure 8. Risk of Bias assessment summary of the included studies (58).

4.2. Study II. Developing Visual Perceptual Skills with Assistive Technology Supported Application for Children with Cerebral Palsy

4.2.1. Results of the MVPT-4 Test

The first research question concerning the MVPT-4 test was: What are the differences in MVPT-4 scores between typically developing and atypically developing children? Based on the literature, we hypothesized that the visual-perceptual skills of children with CP are impaired (31)(79)(80)(81). Our findings supported this hypothesis. The MVPT-4 was used to evaluate whether children with CP demonstrate deficits in visual perception on a motor-free visual perception test. Both baseline and re-test results revealed that children with CP achieved significantly lower mean perceptual quotients compared to typically developing children ($p < 0.001$). These findings are visualized in **Figure 9**.

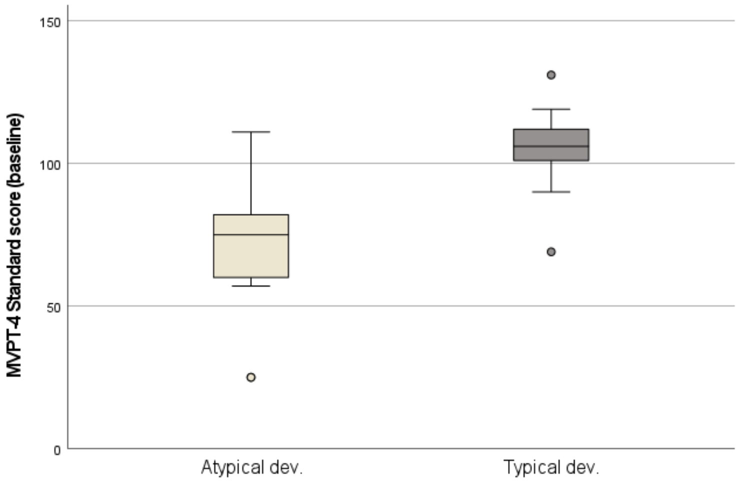

Figure 9. MVPT-4 test results comparison of typically and atypically developing children (43)

The second research question concerning the MVPT-4 test was: How do MVPT-4 scores differ between the intervention group and the control group after the intervention period? We observed promising trends when comparing the differences in baseline and re-test values between the intervention and control groups. However, these differences were not statistically significant (*p* = 0.666) (see **Table 3.**).

Table 3. MVPT-4 test results in both groups at baseline and re-test and the difference of the difference compared to the two groups (pre-post) results (43).

	MVPT-4 test standard score at baseline		**MVPT-4 test standard score at re-test**		**MVPT-4 test standard score difference**	**MVPT-4 test within-group effect**
Group	**Count**	**Median**	**Count**	**Median**	**Median**	**Sig.**
Intervention	9	77	9	101	21.00	0.008*
Control	9	72	9	89	21.00	0.002**
Sig. Mann-Whitney		0.546		0.222	0.666	

*Wilcoxon Signed Rank Test **Paired sample T-test

Within-group comparisons of MVPT-4 test results between the baseline and re-test showed statistically significant differences in both the intervention ($p = 0.008$) and control ($p = 0.002$) groups (see **Table 3.**). The data in the intervention group did not follow a normal distribution, whereas the control group data did, so different methods were used to test significance: the Wilcoxon Signed-Rank Test for the intervention group and the Paired Sample T-Test for the control group.

The third research question concerning the MVPT-4 test was: Are there differences in MVPT-4 scores among children with different CP diagnoses? While the small sample size limited our ability to conduct statistical analyses, dividing the data by CP diagnosis provided insights into subgroup trends. As such, the results are presented as a visualization in **Figure 10.** to highlight potential differences among children with various CP diagnoses.

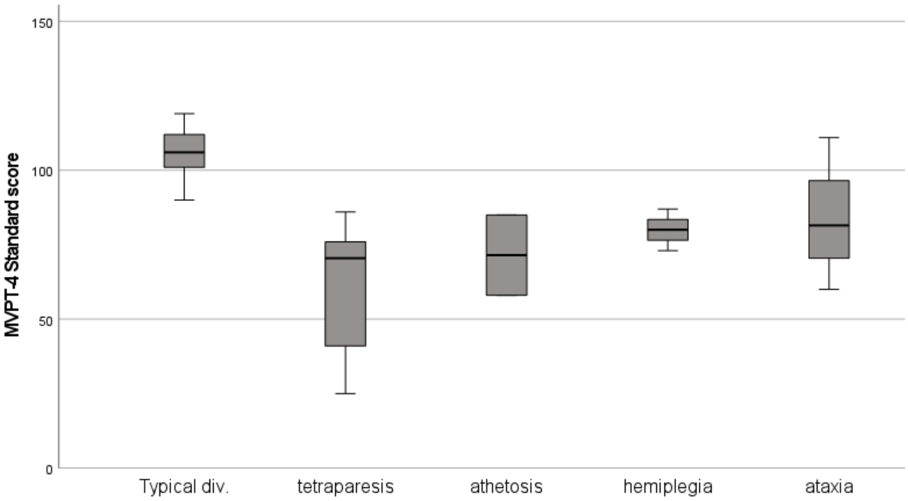

Figure 10. MVPT-4 test results comparison of each CP diagnosis and typically developing participants (N=30) (43).

4.2.2. Results of the Eye-Tracking Data

The test sheets of the MVPT-4 were digitized to enable computerized completion and facilitate the capture of the gaze patterns of the participants. Since the test does not require a motor response from participants (motor-free), digitization was not expected to influence the results. The Tobii Studio software associated with the eye-tracking device was utilized to design the study and select key outcomes for analysis. This software generated visualizations of gaze patterns and allowed for the export of raw data, including fixation duration, fixation counts, and visit counts on visual stimuli, for statistical analysis. In the current study, the visualization of eye-tracking data provides deeper insights and understanding compared to the results of the statistical analysis. Eye-tracking enhances this paradigm by enabling the analysis of both overall looking time distribution and the precise allocation and timing of eye movements directed toward specific regions within an image (48). The findings highlight changes in the gaze patterns of atypically developing children. **Figure 11**. illustrates the gaze pattern of a typically developing child, showing fixations and saccades during the completion of a digitized MVPT-4 task.

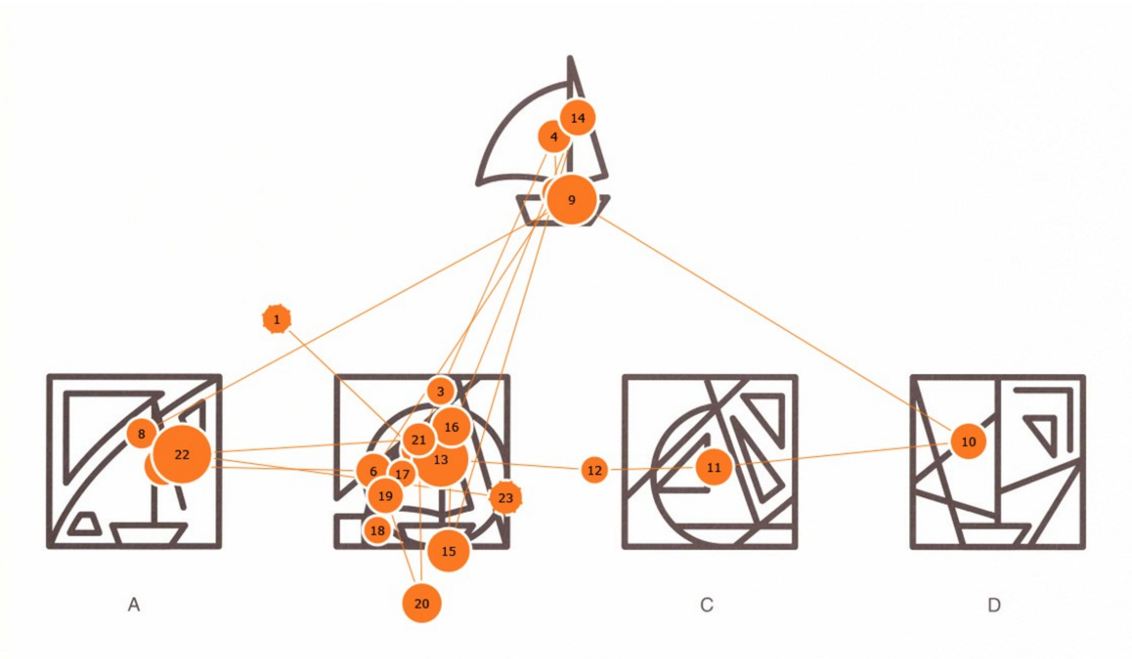

Figure 11. Gaze pattern (fixations and saccades) of a typically developing child

The same visualization illustrates (**Figure 12.**) the scanning pattern of an athetoid child while solving a similar task. The comparison reveals that the scanning pattern of a typically developing child is more orderly and purposeful, with fixations concentrated solely on relevant subjects (shapes). The resolution time for the typically developing child was less than 10 seconds, culminating in a correct response. In contrast, the scanning pattern of the atypically developing child appears more disorganized, with a higher number of fixations in empty spaces. The response time exceeded 35 seconds, and the initial response was incorrect during the first test.

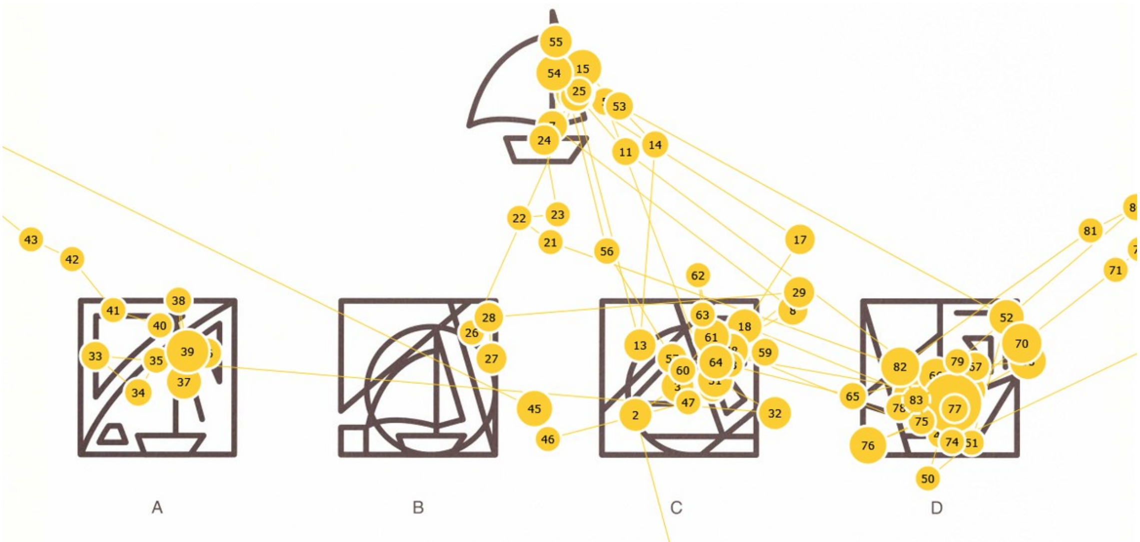

Figure 12. Gaze pattern (fixations and saccades) of an atypically developing child at baseline measurement

Figure 13. illustrates the gaze pattern obtained during the re-test for the same atypically developing child from the intervention group. The comparison indicates positive changes, particularly in visual attention. During the re-test, the child identified the correct item in less time (27 seconds), and the gaze pattern appeared more organized than in the initial test.

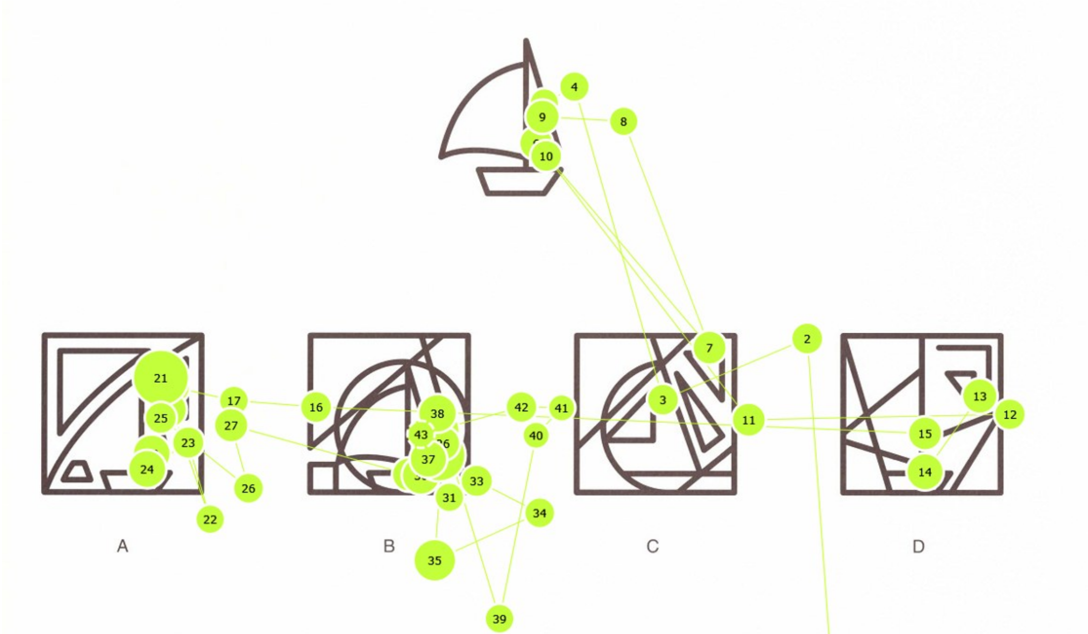

Figure 13. Gaze pattern (fixations and saccades) of an atypically developing child at re-test after intervention

Heat maps visualize how visual attention is distributed across a stimulus, effectively highlighting focus areas (hot spots) and viewing behavior for a group of participants. Gaze plots provide details on the location, order, and fixation time spent on different zones of the stimulus (82). **Figure 14. and 15.** illustrates the heat map of all typical (N=12) and all atypical (N=18) developing participants.

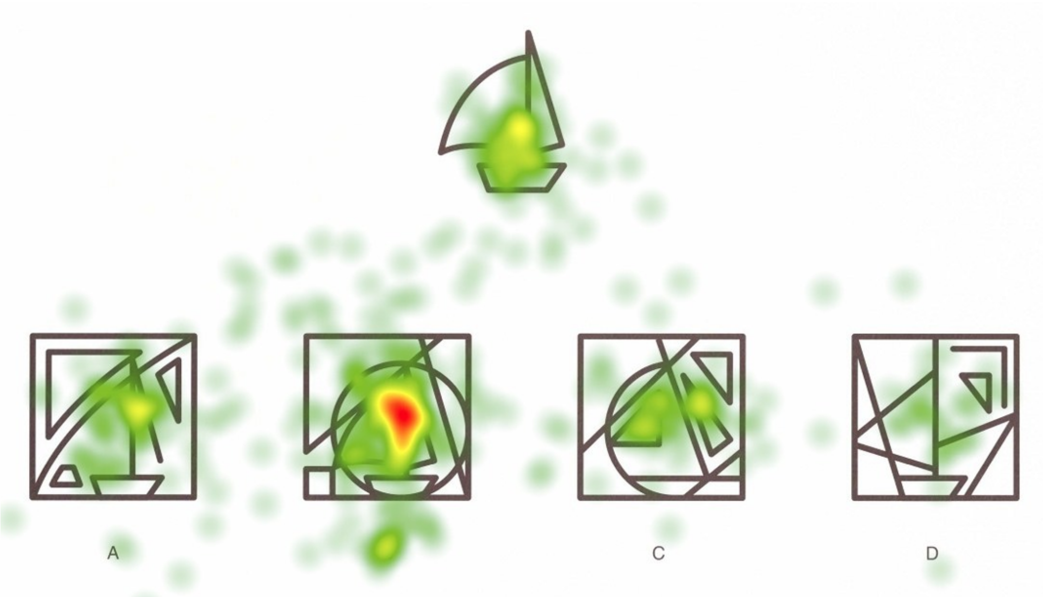

Figure 14. Gaze pattern (heat map) of all typically developing children

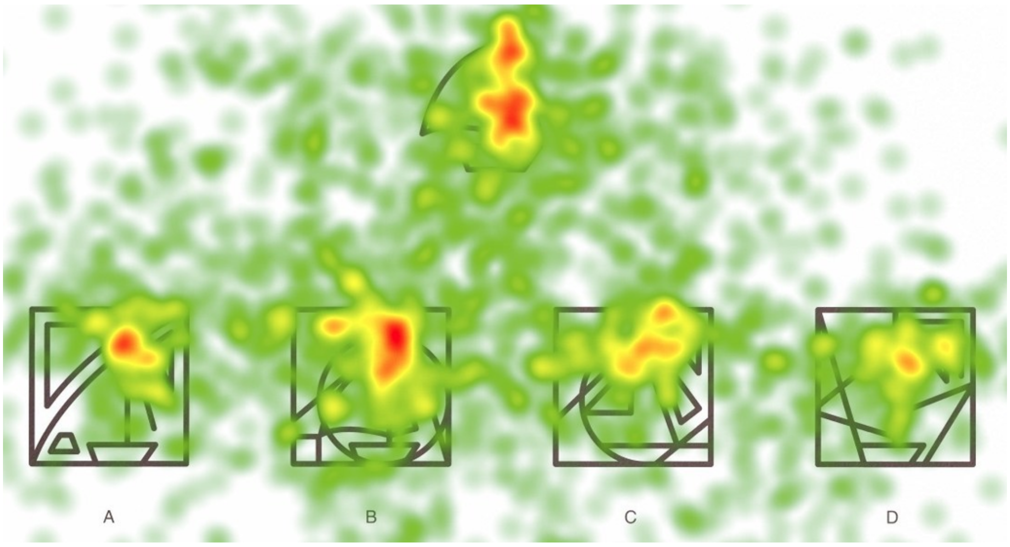

Figure 15. Gaze pattern (heat map) of all atypically developing children at baseline measurement

The two heatmaps generated from eye-tracking data illustrate clear differences in gaze patterns between the two groups. In the typically developing group, fixations are predominantly concentrated on the target stimulus and the correct response option. In contrast, the gaze patterns of atypically developing children appear more dispersed, with fixations distributed unevenly across multiple images.

Areas of interest (AOI) were defined within the digitized MVPT-4 test sheets, including target stimuli, correct stimuli, and incorrect stimuli (**see Figure 16**.).

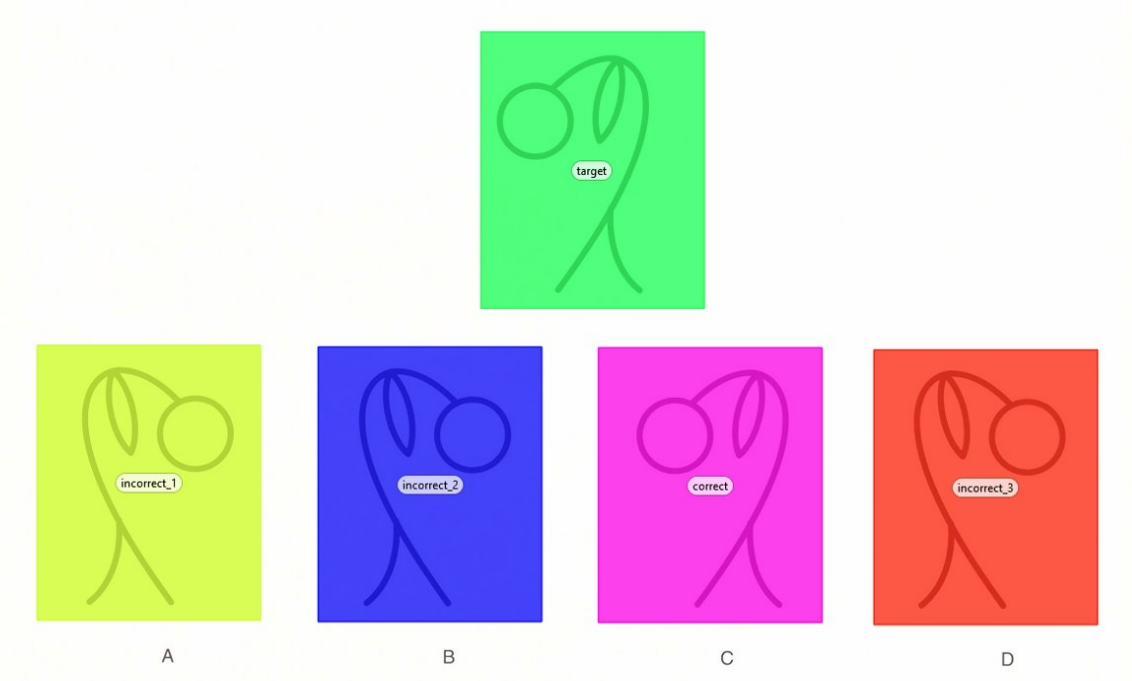

Figure 16. An example of defining AOI-s for MVPT-4 subtask ("object and figure matching")

To manage the extensive dataset generated from the AOI analysis, one sheet from each type of subtest was selected for detailed evaluation. Data comparisons were conducted in multiple ways, including an analysis of differences between the "typically" and "atypically" developing groups. Significant differences were observed in a few specific subtests; however, no consistent patterns were identified in the AOI parameters across the datasets. The results of the selected test task ("object and figure matching") (**Figure 16.**) are presented below for the correct stimuli area, focusing on total fixation duration (TFD) (p = 0.006), fixation count (FC) (p = 0.004), and visit count (VC) (p = 0.005). **Figure 17.** illustrates the TFD in seconds. The data are presented for typically and atypically developing participants. Atypically developing participants exhibit longer fixation durations compared to their typically developing peers, highlighting a potential difference in cognitive processing patterns.

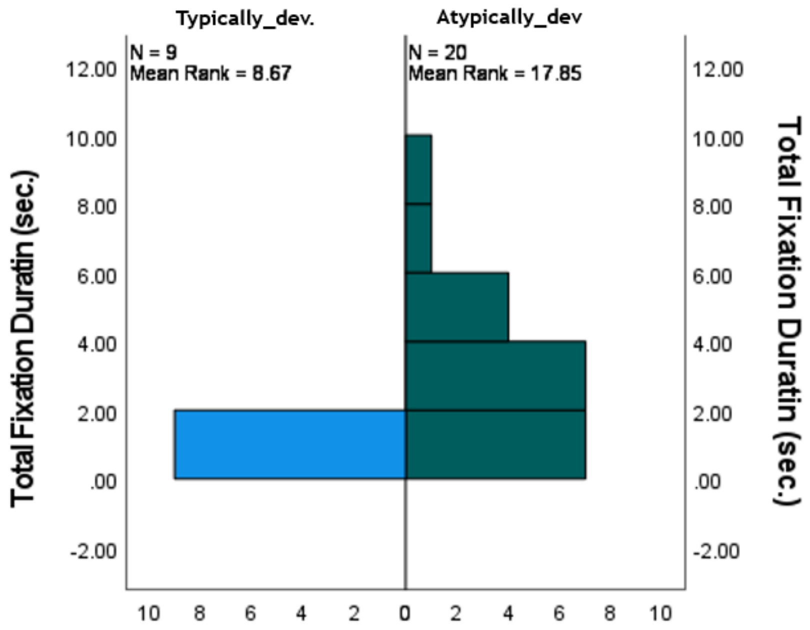

Figure 17. Total Fixation Duration (TFD) on Correct Answer AOI-s Between Typically and Atypically Developing Groups

Despite a thorough analysis of the AOI data, no statistically significant differences or distinct gaze patterns were identified between the intervention and control groups. Variables such as TFD, FC, and VC showed no measurable variation across the two groups.

5. DISCUSSION

5.1. Discussion of the findings regarding WBV therapy

Due to the diverse symptoms associated with cerebral palsy (CP), holistic approaches are essential in addressing the condition. The systematic review and meta-analysis presented here aim to examine the potential short- and long-term effects of combined whole-body vibration (WBV) therapy (as an additional intervention) and conventional physiotherapy on the musculoskeletal system in children with CP.

Abnormal muscle tone—whether increased or reduced—is one of the most significant symptoms of cerebral palsy (CP), making movement difficult or even impossible. Five studies (59), (61), (63), (69), (70) assessed spasticity using the Modified Ashworth Scale (MAS), which is known as a clinical measure of muscle spasticity in people with neurological conditions (76). The results showed no significant differences in spasticity between the intervention and control groups after treatment. However, a positive trend was observed, indicating a slight decrease in muscle tone. Studies that included follow-ups reported that WBV treatment might reduce spasticity in patients with CP temporarily rather than permanently. Additionally, one study (61) reported that the effects of decreased tone could last for up to three days following the intervention. A noteworthy study reported that the effects of WBV on spasticity can persist for at least eight days, as evidenced by a significant reduction in quadriceps spasticity following a WBV intervention among individuals with spastic hypertonia. Interestingly, spasticity was further reduced during the delayed post-WBV test compared to the immediate post-WBV test. This suggests that WBV may provide prolonged benefits for spasticity management, regardless of the use of antispastic agents (83). Another study demonstrated that a single session of WBV temporarily improves spasticity in the ankle plantar flexors, with effects lasting only 1–2 hours in children with CP. These findings suggest that the impact of WBV on spasticity is short-term and not sustained over longer periods (84).

The meta-analysis identified significant improvements in walking-related outcomes. While all studies reported positive changes in walking parameters, statistically significant changes were found only in two assessed outcomes: walking speed ($p = 0.02$) and step length ($p = 0.05$). The effects of WBV therapy on walking abilities were also evaluated using additional methods, such as the GMFM E domain (gait activities), the 6-Minute Walk Test (74), and the Time Up and Go Test (75). On the one hand, this diversity in measurement approaches is advantageous, as it demonstrates through multiple methods that WBV therapy improves walking ability. On the other hand, using different assessment methods for the same expected outcome complicates the statistical analysis of metadata.

It is important to note that walking-related outcomes were predominantly examined in participants with milder CP diagnoses (hemiparesis, diparesis) and classifications (GMFCS I-III). For more severe cases of CP, no outcome measures were conducted for this variable. Furthermore, significant changes in walking outcomes were mainly reported in studies involving participants classified within the milder GMFCS I-II categories.

Another related outcome was the assessment of overall stability or balance, which was evaluated in four studies (12), (59), (70), (77). However, using different measurement methods did not allow for statistical analysis. Two studies reported statistically significant improvements in balance skills favoring the WBV group.

Children with CP often experience reduced muscle strength and control, limiting their ability to perform functional tasks such as standing and walking (70). Four studies (12), (62), (63), (72) assessed muscle strength as an outcome, with three utilizing a dynamometer to measure knee extensor strength in Newtons (N). While the difference between the WBV intervention group and the control group was not statistically significant, a positive trend was observed. The strong correlation between gait speed and muscle strength in patients with CP is well-documented (61), (85), and the significant improvements in gait speed-related outcomes found in this meta-analysis further support this relationship.

Muscle-strengthening interventions are essential for rehabilitating weakened muscles. Enhancing the strength of lower extremity muscle groups has the potential to improve their workload capacity and endurance, which are often diminished due to neurological injury and reduced activity. Additionally, increased muscle strength can lead to improvements in walking speed, contributing to enhanced functional mobility for children with cerebral palsy. (86). WBV therapy has been shown to increase muscle strength and force, potentially leading to improvements in neuromuscular capacity.

Gross motor function is a commonly measured outcome, with nearly half of the selected studies utilizing the Gross Motor Function Measure (73) to assess participants' functional skill levels. All these studies reported positive changes, with most showing statistically significant improvements in one or two domains or total GMFM scores. The results also revealed notable, though statistically nonsignificant, changes between WBV training and control groups, with mean differences of 2.80 in the D-domain (standing) and 5.74 in the E-domain (walking, running, and jumping). According to Wang and Yang, a change score of 1.3 points on the GMFM-88 reflects clinically relevant improvement, while a score of 3.7 points distinguishes between great and moderate improvement (87).

Since the last systematic review and meta-analysis on this topic in 2015 (15), there has been a significant increase in the number of randomized controlled trials (RCTs) conducted on this topic. The earlier analysis included only six studies, whereas the current review incorporates sixteen. This expanded dataset allows for a more comprehensive evaluation of the effects, covering a broader range of outcome measures, including walking and gross motor function-related skills.

5.1.2. Limitations

Efforts were made during the data pooling process to minimize heterogeneity; however, several challenges complicated the meta-analysis. These included inconsistent or insufficient data reporting, variations in measurement methods, undefined patient populations (e.g., unpublished GMFCS levels), small sample sizes, and diverse intervention designs. These factors significantly impacted the ability to perform robust analyses. Although subgroup analyses based on CP subtypes or GMFCS categories were initially planned, the heterogeneity of the study populations and the limited number of studies assessing specific outcomes rendered such analyses unfeasible. Additionally, the use of correlation imputation and the estimation of the mean and standard deviation from quartiles, while widely accepted in meta-analyses (41), introduces limitations as these methods provide only approximations of the true values. These estimations may influence the precision of the findings and should be considered when interpreting the results.

5.2. Discussion regarding Visual Perceptual Skills Development

We created and applied special educational software for children with CP to develop their visual perceptual skills. CP is frequently associated with cognitive dysfunctions, including deficits in visual perceptual skills, which can contribute to broader cognitive disabilities (31), (79), (80), (81). The findings of our study reinforce this association, as the MVPT-4 assessment results revealed that children with CP (N = 19) scored significantly lower on mean perceptual quotients ($p < 0.001$) compared to their typically developing peers (N = 12). These results highlight the critical role of assessing visual perception as part of cognitive evaluations in children with CP. Moreover, the MVPT-4 proved to be a reliable and valuable tool for this purpose, offering insights into the visual perceptual abilities of this population.

This study also aimed to investigate the long-term effects of the educational applications developed on the visual perceptual skills of children with CP. While the effect size did not reach statistical significance, the observed differences are promising, suggesting that such applications could be beneficial if integrated into special education programs. The significant differences observed between baseline and re-test scores in both the intervention ($p = 0.008$) and control ($p = 0.002$) groups suggest that visual perceptual skills develop rapidly during this critical developmental period. However, the limited sample size of the intervention group poses a challenge to achieving statistically robust results, but small samples are not uncommon in studies involving children with CP. Another important aspect of this study was the digitalization of the MVPT-4 test sheets, which enabled computerized completion and the capture of participants' gaze patterns using eye-tracking technology. A key insight is that eye-tracking can be very useful in assessments involving children with severe CP, including those with communicational deficits. The technology provides valuable feedback not only after the test but also during its administration. Eye-tracking allows for real-time monitoring of visual attention and fixation points, offering insights into whether the child understands the task and whether their attention is focused on the relevant stimuli. This capability is particularly beneficial when working with nonverbal children, as it helps infer their comprehension and engagement without requiring verbal communication. Incorporating eye-tracking into such assessments enhances the accuracy and depth of data collection, making it a promising tool for further studies on visual perceptual skills in children with CP. The visualized eye-tracking results provide additional insights. Changes in gaze patterns, such as more organized fixations on relevant subjects in the intervention group, suggest positive effects on visual attention.

Eye-tracking AOI data indicate that typically developing participants spend less time viewing the images and stimuli, resulting in fewer fixations and much faster task completion. However, visualizations derived from eye-tracking effectively illustrate the differences in gaze patterns between the intervention and control groups, as well as the positive changes in the organization of gaze patterns following the intervention. The absence of statistically significant differences in AOI metrics between the intervention and control groups mirrors the findings of the MVPT-4 test results. This suggests that the intervention, while showing promising tendencies, did not produce statistically measurable changes in gaze behavior or visual perceptual skills within the study's timeframe and sample size.

5.2.2. Limitations

Our main limitation is the small and heterogeneous sample size, which reduces the statistical power and generalizability of the findings. Recruiting larger samples in future research would enhance the robustness of the results. The lack of statistically significant differences between the intervention and control groups may be partly attributed to the natural progression of visual perceptual skills during childhood, as indicated by the significant improvements in both groups. Another challenge is measuring the application-generated effect on visual perceptual skills, as children - particularly those with atypical development - receive various therapies and educational interventions daily. This introduces potential confounding variables that make it difficult to isolate the specific impact of the applications. Our data analysis further confirmed that this childhood period is highly progressive in cognitive and physical development, adding complexity to interpreting intervention effects.

6. CONCLUSION

In the systematic review and meta-analysis, we comprehensively examined and aggregated all available CP-related outcomes to evaluate the impact of WBV therapy. Significant improvements were observed in two walking-related outcomes—walking speed and step length—while nonsignificant but clinically meaningful positive changes were noted in several musculoskeletal outcomes. The findings suggest that patients with milder forms of CP (GMFCS I-II) tend to experience more substantial benefits from WBV therapy, as supported by significant results primarily related to walking and balance.

Based on the findings, a clear assessment of the usefulness of this intervention cannot be made; nonetheless, due to the promising results, it would be worthwhile to conduct additional RCTs to enhance the available evidence in this field. Additionally, this review highlights a notable gap in the literature, as very few studies included patients with severe impairments, and none involved GMFCS V-level patients. Investigating the effects of WBV therapy on the most severe CP cases could provide valuable insights and represent an important avenue for future research. Furthermore, future research should focus on investigating the short-term effects of WBV therapy on spasticity, particularly immediately after the intervention, to better understand its immediate benefits.

Emerging technologies, such as focal muscle vibration therapy, offer new possibilities for more targeted vibration applications. Exploring these advancements could enhance the precision and effectiveness of vibration therapy, providing further opportunities to refine its integration into therapeutic programs for children with CP.

Our other research highlights the importance of addressing visual perceptual deficits in children with CP and demonstrates the value of integrating technology-supported applications into special education programs. While the effect size was not statistically significant, the observed improvements suggest that such interventions hold promise for enhancing visual perceptual and attention skills. The findings also reaffirm the strong relationship between physical condition and visual perceptual abilities, emphasizing the need for holistic approaches in intervention planning.

The integration of eye-tracking technology provides valuable insights into the visual attention and task comprehension of children with serious forms of CP and communication deficits, highlighting its potential as a supportive tool in future assessments and interventions.

Further research with larger sample sizes and longitudinal designs is necessary to fully understand the potential of technology-supported applications in improving cognitive and visual skills. This study contributes to the growing body of evidence that underscores the role of assistive technology in supporting children with CP.

7. SUMMARY

This thesis investigates innovative interventions targeting musculoskeletal and cognitive outcomes in children with cerebral palsy (CP), addressing new therapies in current rehabilitation approaches. CP is a complex condition primarily characterized by motor impairments, often accompanied by cognitive deficits, including visual perceptual impairments (VPI).

Two studies were conducted to explore interventions for children with CP. The first study involved a systematic review and meta-analysis of whole-body vibration (WBV) therapy. Eighteen randomized controlled trials (RCTs) were analyzed, focusing on the impact of WBV on musculoskeletal outcomes. The second study assessed the effectiveness of a specially developed educational application targeting visual perceptual (VP) skills. A matched-pair RCT was conducted, with 18 participants randomly assigned to intervention and control groups. VP was measured using the MVPT-4, complemented by eye-tracking technology to analyze gaze patterns.

The WBV meta-analysis revealed significant improvements in walking-related outcomes (e.g., walking speed and step length), with nonsignificant but clinically meaningful changes observed in other musculoskeletal outcomes, such as gross-motor functions, spasticity, and balance. However, variations in WBV protocols, including frequency, duration, and exercise positions, presented challenges for standardization.

In the educational application study, both intervention and control groups showed significant improvements in MVPT-4 scores, reflecting the natural developmental progression of VP during childhood. Eye-tracking results indicated positive changes in gaze patterns, with participants in the intervention group displaying more organized fixations, suggesting enhanced visual attention.

The findings support the potential of WBV as an additional therapy for improving musculoskeletal outcomes in children with CP. The educational application demonstrated promise as a tool for enhancing VP skills, with assistive technologies such as eye-tracking enabling accessibility for children with severe physical disabilities. These studies underscore the importance of integrating innovative interventions and technologies into therapy programs for children with CP.

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10. ACKNOWLEDGEMENTS

I have been fortunate to receive many valuable support from many individuals throughout my scientific journey and the preparation of this dissertation. I would like to express my deepest gratitude to those whose contributions made this work possible.

First and foremost, I would like to express my heartfelt gratitude to my supervisors, Dr. Ibolya Túri and Dr. Éva Feketéné Szabó, whose unwavering support and expert guidance were instrumental in the successful completion of this research and thesis.

I am deeply thankful to all the co-authors of our articles for their invaluable contributions, especially Dr. Rita Nagy, who provided scientific and methodological supervision for the systematic review and meta-analysis project, and Nóra Zimonyi, whose assistance during the selection process was invaluable.

I extend my sincere thanks to the patients, colleagues, caregivers, and investigators who made the second project possible with their dedication and collaboration.

On a personal note, I am profoundly grateful to my family and friends for their continuous encouragement throughout my Ph.D. journey. A special thank you goes to my wife, Sára, and my three sons, for their enduring support and patience.

Lastly, I would like to acknowledge the use of large language models, such as Grammarly and OpenAI's ChatGPT, for assistance in refining the English language and grammar of this dissertation. These tools were utilized solely for non-creative, mechanical suggestions and did not influence the originality or integrity of the research findings.