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The use of virtual reality technologies in children with adverse health conditions: can it improve neuromotor function? a systematic review of randomized clinical trials

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Objective: To synthesize information on use of virtual reality (VR) technologies for improving neuromotor outcomes in children with adverse health conditions, focusing exclusively on randomized clinical trials.
Methods: The included studies followed the PICOS strategy, adhered to the methodology suggested by the PRISMA method, and complied with the protocol CRD42023416757 on the PROSPERO platform. Two databases were explored, and data collection was completed on 6 July 2024. The selected articles for this review underwent a methodological bias analysis by Joanna Briggs.
Results: A total of 824 studies were identified. After analysis using the PRISMA method and application of eligibility criteria, nine studies comprised this systematic review. Data from 260 children of both sexes were analysed across three distinct adverse health conditions: developmental coordination disorder, cerebral palsy, and autism spectrum disorder. The articles correspond to the period between 2012 and 2022. Overall, the studies reported positive outcomes regarding improvements in the neuromotor system following virtual reality-based interventions. Manual dexterity improved in two studies, while enhancements were also observed in gross and fine motor skills, balance, and trunk control.
Conclusion: According to this systematic review, motor skills may benefit from virtual reality-based interventions in children with cerebral palsy, developmental

coordination disorder, and autism spectrum disorder. Domains such as manual dexterity, balance, motor coordination, and reaction time showed consistently positive outcomes.

KEYWORDS

VR, active video game, exergames, child, children, motor performance, motor skill, motor rehabilitation

Introduction

Sedentary behavior is a risk factor for all-cause mortality and cardiovascular diseases in adulthood (Tremblay et al., 2010). During childhood, the lifestyle developed tends to persist into adulthood, making this stage a critical period for adopting a healthy lifestyle (Yu and Zou, 2023). Adopting healthy habits may include, for example, reducing time spent in sedentary behaviors through increased regular physical activity.

A promising strategy that has gained prominence in the approach to physical activity is Virtual Reality (VR) technology (Peng et al., 2015). In summary, a virtual environment or VR is a simulation of the real world or a projection of a fictional world, generated by computational software that promotes interaction between the individual and the machine (Holden, 2005). VR utilizes technologies such as head-mounted displays, desktop computers, capture systems, motion tracking, and motion-detection gloves to mediate not only interaction but also immersion in computer-generated realities (Zanatta et al., 2023).

In this context, with the technological advancements in healthcare, bolstered by the current digital culture, physical activity is also being utilized as a therapeutic function. It has been integrated into supervised electronic interaction programs, constituting an important alternative for the treatment of cardiovascular diseases (Hammer et al., 2023) and depression (Fernandes et al., 2022). Consequently, commercial electronic games, serious games, and specific VR software have become important health tools, as they allow for human-machine interaction while providing real-time biofeedback (Perez-Marcos, 2018).

The provision of sensor-cognitive-motor stimuli is positive and enhances the use of VR in various adverse health conditions, particularly those that impair the functions of the neuromotor system. These conditions are associated with issues such as reduced autonomy, difficulties in performing daily tasks, and limitations in mobility (Rutkowski et al., 2020). Aiming to understand the improvement of the neuromotor system through VR, this review seeks to synthesize information on the use of VR technologies for exergames in enhancing neuromotor outcomes in children with adverse health conditions, utilizing only randomized clinical trials.

Methods

This systematic review adopted the criteria recommended by the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as shown in Figure 1. The protocol was registered on 25 April 2023, in the International Prospective Register of Systematic Reviews (PROSPERO) database, obtaining the registration number CRD42023416757.

Search strategy

Searches were conducted in the databases PubMed (MEDLINE) and PsycINFO using the following keywords: VR, active video game, exergames, child, children, motor performance, motor skill, and motor rehabilitation.

For the PubMed (MEDLINE) database, the following search equation was used: ((((((virtual reality) OR (active video game)) OR (Exergaming)) OR (exergames)) AND (Movement disorder)) OR (neuromotor disorder)) AND (Child). For the PsycINFO database, the search terms were: Any Field: virtual reality OR Any Field: active video game OR Any Field: Exergaming OR Any Field: exergames AND Any Field: Movement disorder OR Any Field: neuromotor disorder AND Any Field: Child AND Age Group: School Age (6–12 years) AND Methodology: Clinical Trial.

The last search was conducted on 6 July 2024, and the results from all databases were compiled in RIS format, and then saved in the virtual library of the reference management software Mendeley (Mendeley version 1.19.8).

Selection of studies and eligibility criteria

Two independent researchers (ABJS and RFS) read all titles by database and abstracts, and the articles that met the review criteria were read in full. The presence of a third researcher (WMB) was requested in cases of disagreement. The studies included in this review followed the following criteria: randomized clinical trials and studies involving children until 12 years old with any adverse health condition who were exposed to treatments involving virtual reality aimed at improving the neuromotor system. Studies were excluded if they: a) did not assess outcomes in the neuromotor system; or b) included only healthy children.

Regarding study selection, the PICOS strategy was used as proposed by Amir- Behghadami and Janati (2020). The population (P) consisted of children with adverse health conditions; the intervention of interest (I) was the use of VR in motor rehabilitation or motor training; for comparison (C), articles that utilized and did not utilize VR-based interventions were selected; the outcomes (O) analysed were those related to the neuromotor system; and we included only studies (S) that were randomized clinical trials.

Data extraction and synthesis strategy

The records from the searches were imported into a Mendeley library (Mendeley 1.19.8), and duplicates were removed. Excel (Microsoft, 2003) was used to extract data from the included studies. Data extraction was conducted independently by two reviewers using a standardized pre-prepared form in Word. In

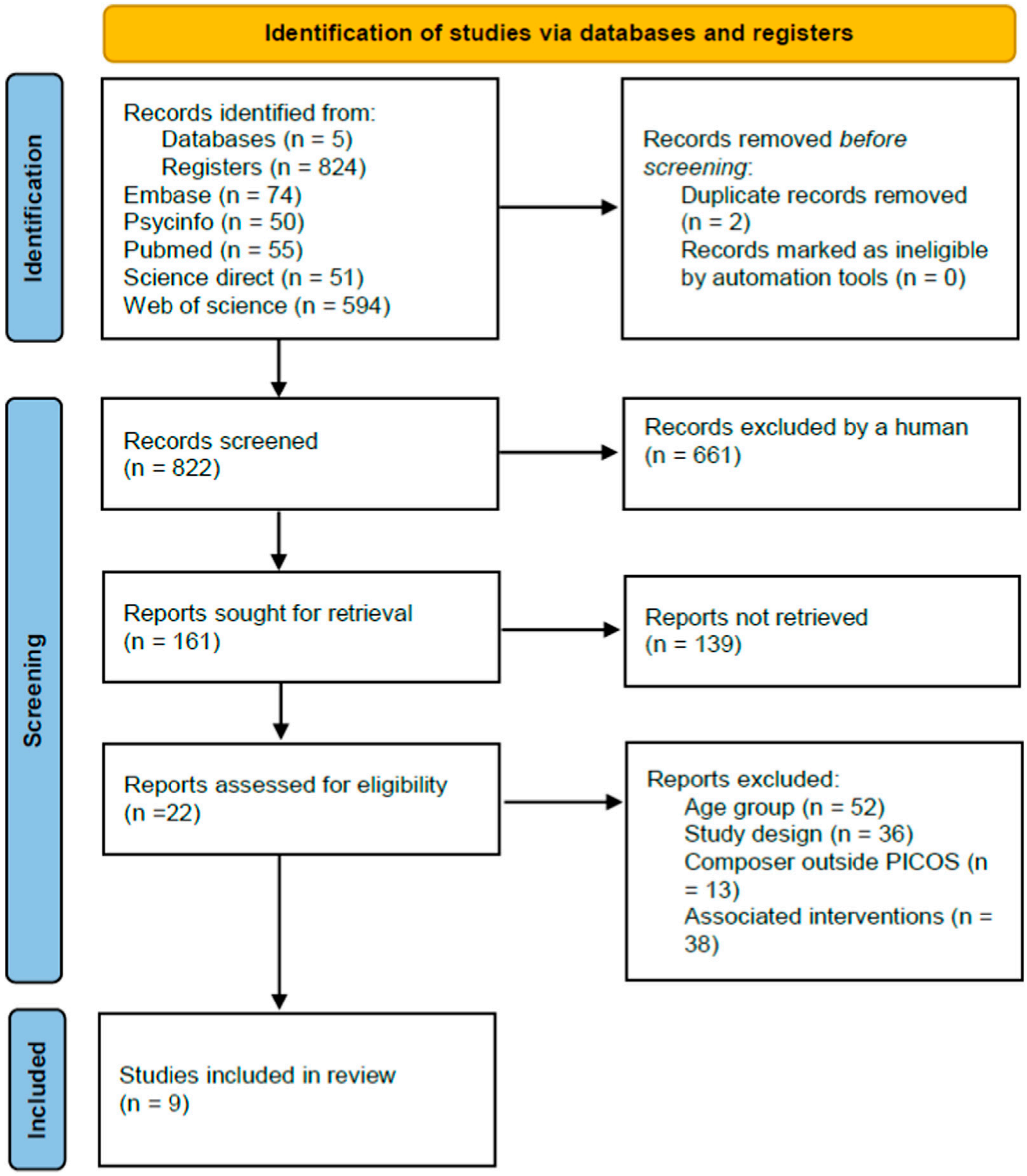

FIGURE 1
Flowchart of identification of studies via databases.

cases of disagreement between the reviewers, a third reviewer assisted in the decision.

To synthesize the data, the information was organized into pre-established tables containing details about the authors, year of publication, sample characterization, study design, characterization of the VR intervention, characterization of the VR equipment, neuromotor outcomes, and study conclusions, in both Word and Excel formats.

Risk of bias

The Joanna Briggs Institute (2014) was used to assess the quality of the included studies, where each study was categorized according to the percentage of positive responses to the questions corresponding to the assessment instrument. As a complementary analysis of the risk of bias, RevMan 5.3.0 software was used to detect intervening factors based on the seven judgment criteria provided by the program, which are: Random Sequence Generation, Allocation Concealment, blinding of participants, and personnel, Blinding of outcome assessment, Incomplete outcome data, Selective reporting, and other bias. Thus, this review presents a low risk of bias, as shown in Figures 2, 3.

Results

In this study, a literature search was conducted in two databases (PubMed/MEDLINE and PsycINFO) to obtain information on the

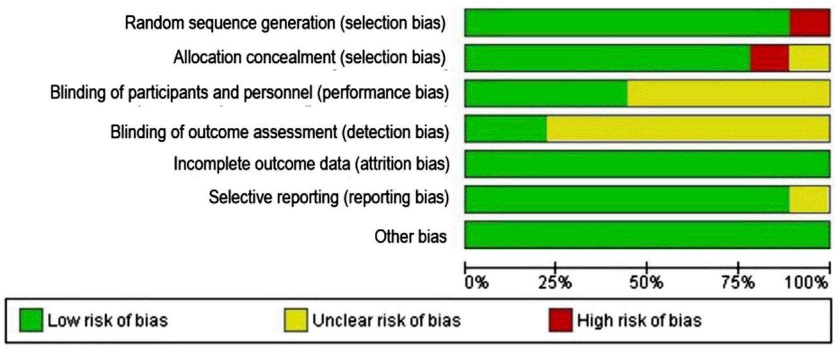

FIGURE 2
Risk of bias graph.

use of VR technologies in improving outcomes in the neuromotor system in children with adverse health conditions. After applying the eligibility criteria, nine studies were included (AlSaif and Alsenany, 2015; Chen et al., 2012; 2013; EbrahimiSani et al., 2020; Lu et al., 2018; Meyns et al., 2017; Pourazar et al., 2018; Romano et al., 2022; Şahin et al., 2020). The complete information about the exclusions is presented in Figure 1.

The synthesis of the gathered information was collected from 260 participants in a cumulative sample size from the nine studies. Two studies were conducted in Taiwan (Chen et al., 2012; Chen et al., 2013), two in Iran (EbrahimiSani et al., 2020; Pourazar et al., 2018), one in Italy (Romano et al., 2022), one in Turkey (Şahin et al., 2020), one in Netherlands (Meyns et al., 2017), and one in Saudi Arabia (AlSaif and Alsenany, 2015). The country in which the intervention was conducted could not be identified in the study by Lu et al. (2018).

The age ranges comprised between 6 and 12 years, and all studies included at least one treatment group and one control group. The adverse health conditions identified in the studies included in this synthesis were: developmental coordination disorder (EbrahimiSani et al., 2020), cerebral palsy (Chen et al., 2012; Chen et al., 2013; AlSaif and Alsenany, 2015; Pourazar et al., 2018; Şahin et al., 2020; Romano et al., 2022; Meyns et al., 2017), autism spectrum disorder (Lu et al., 2018). Additional information can be found in Table 1.

The analysed studies showed a wide variability in the duration of the interventions, with the shortest being 4 weeks (Pourazar et al., 2018; Lu et al., 2018), while the most frequent duration was 12 weeks (Romano et al., 2022; AlSaif and Alsenany, 2015; Chen et al., 2012; Chen et al., 2013). When considering the total cumulative minutes of sessions, the shortest total time was from Pourazar et al. (2018) and Lu et al. (2018), which totaled 300 min. In contrast, the longest time was 1,440 min (Chen et al., 2012; Chen et al., 2013) (Table 1).

Regarding the location of the intervention delivery, 55.5% (5/9) took place in the participants' homes. The clinical trials conducted by EbrahimiSani et al. (2020) and Lu et al. (2018) were carried out in school settings. Meanwhile, the studies by Pourazar et al. (2018) and Şahin et al. (2020) were conducted in a rehabilitation clinic. As for the most commonly used test among the analyzed studies, the Bruininks-Oseretsky test of Motor proficiency stood out.

The analyzed studies (AlSaif and Alsenany, 2015; Chen et al., 2012; 2013; EbrahimiSani et al., 2020; Lu et al., 2018; Meyns et al., 2017; Pourazar et al., 2018; Romano et al., 2022; Şahin et al., 2020) showed positive results regarding improvements in the neuromotor system following virtual reality-based interventions. Manual dexterity improved in two studies: Romano et al., 2022 ($\Delta TG = 3$ vs. $\Delta CG = -2.6$, $p = 0.01$) and AlSaif and Alsenany, 2015 ($TG = 17.3$ vs. $CG = 11.3$). Gross and fine motor skills showed improvements (Şahin et al., 2020), with balance specifically demonstrating greater gains in the treatment group ($M = 16.1$) compared to the control group ($M = 12.7$) (AlSaif and Alsenany, 2015), along with gains of up to 17 points on the trunk control scale (Meyns et al., 2017). The complete information regarding the synthesis of the results can be found in Table 2.

Discussion

This systematic review synthesizes information on the use of virtual reality (VR) to enhance neuromotor function in children with various neuromotor disorders. Data from 260 children and adolescents of both sexes analyzed across three distinct health outcomes: cerebral palsy, developmental coordination disorder, and autism spectrum disorder. VR use showed more consistent improvements among participants with cerebral palsy. Although the limited number of included studies is acknowledged, the evidence observed in these individuals spans multiple muscle groups, motor skills, and physical abilities.

The findings for each disorder are discussed in detail below. We begin with the most represented condition in the reviewed literature.

Cerebral palsy

William John Little first documented cerebral palsy (CP) in 1843 and is currently one of the most prevalent childhood disabilities worldwide, affecting two out of every 1,000 live births. It is characterized by abnormal brain development, which can impact the neuromuscular, sensory, perceptual, cognitive, and/or behavioral systems (Brasil, 2013). This dysfunction can be classified based on the predominant clinical presentation, as follows: (a) spastic–characterized by increased muscle tone; (b) dyskinetic–marked by highly variable muscle tone; and (c)

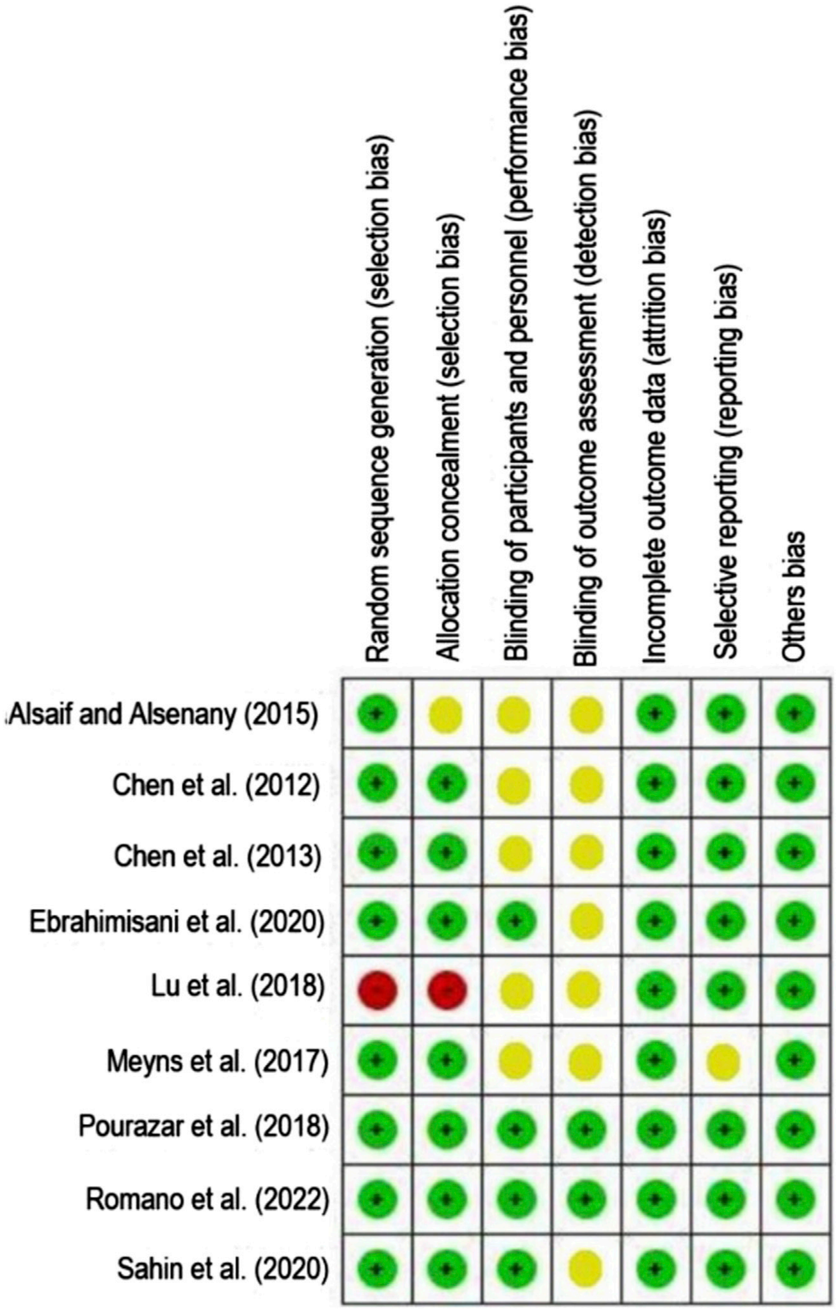

FIGURE 3
Risk of bias summary.

ataxic–characterized by impaired movement coordination (Himpens et al., 2008).

In this review, seven out of the nine analyzed studies were conducted with participants diagnosed with either spastic or ataxic cerebral palsy. The studies by Şahin et al. (2020) and Pourazar et al. (2018), included children with spastic cerebral palsy with unilateral anatomical distribution, while AlSaif and Alsenany (2015) and Meyns et al. (2017) included children with bilateral spastic distribution. On the other hand, Chen et al. (2012), Chen et al. (2013) did not specify the anatomical distribution; instead, they classified participants according to levels I and II of the Gross Motor Function Classification System (GMFCS). Romano et al. (2022) was the only study to include children with ataxic cerebral palsy.

It was observed that children with spastic cerebral palsy and unilateral anatomical distribution experienced positive and significant improvements in motor proficiency, running, balance, strength, upper limb coordination, gross and fine motor functions, as well as in simple and discrimination reaction times. Conversely, studies examining the use of VR in cases of cerebral palsy with bilateral anatomical distribution did not identify significant improvements in the neuromotor outcomes assessed.

TABLE 1 Description of the studies.

Authors and year	Participants		Participants/ Groups		Aim	Adverse health condition	Description of the intervention
	n	*Age*	*CG*	*TG*			
Romano et al. (2022)	18	5–17 years old	9	9	To describe the effect of a home-conducted exergame-based exercise training for upper body movements control	Ataxia	The study evaluated a home rehabilitation program using the Niurion® exergame system for children with ataxia. The kit, comprising motion sensors and interactive software. The intervention protocol required children to complete daily sessions of approximately 1 hour, five times per week for 12 weeks, totaling 60 sessions. Meanwhile, the CG maintained their usual conventional physiotherapy routine, consisting of a 45-min session once a week, with no changes to their therapeutic regimen
Ebrahimisani et al. (2020)	40	7–10 years old	20	20	To improve predictive modeling through training in the VR environment, and to examine the effect of a course of a VR training program on the predictive motor control functions	DCD	The intervention program used the Xbox Kinect 360 system for motor training. Conducted over 8 weeks, the program included two 30-min sessions per week and took place in a school setting, utilizing four Kinect Sports games selected for their specific motor control demands. Each session was divided into three stages: a warm-up (3–5 min), the main training, which consisted of two games chosen by the child (12 min each), and a cool-down (2–3 min). The CG did not receive any intervention
Şahin et al. (2020)	60	7–16 yeras old	30	30	To investigate the effects of VR through Kinect on both gross and fine motor functions and independence in daily living activities	Unilateral spastic cerebral palsy	The intervention consisted 16 sessions of 45 min each (2 times per week for 8 weeks) using 5 Kinect games. The CG received only neurodevelopmental therapy twice a week (for 8 weeks), focused on motor skills
Pourazar et al. (2018)	30	7–12 years old	15	15	To investigate the training effects of a VR-based intervention on react time	Spastic hemiplegic cerebral palsy	The Xbox 360 Kinect was utilized as an intervention device, specifically employing bowling and golf games for rehabilitation purposes. The intervention was structured as a 12-session program, conducted three times a week over 4 weeks, with each session lasting approximately 25 min. Each session was divided into two 10-min blocks of gameplay (5 min for each game – bowling and golf), separated by a 5-min rest interval between the blocks. Meanwhile, the CG maintained their routine of conventional therapy, without the incorporation of VR in their treatment
Lu et al. (2018)	12	8–16 years old	7	5	To describe our effort on virtual pink dolphins to assist children in their learning	Autism Spectrum Disorder	The study developed a VR game called "Pink Dolphins Virtual" using the Kinect platform for motion detection in an immersive 3D environment. In the game dynamics, children took on the role of dolphin trainers, replicating arm gestures that were mirrored by a virtual avatar to command the dolphins. The game was structured in phases: beginning with a warm-up round featuring visual and verbal instructions, followed by three progressively challenging levels - the Triangle stage (1 action per set), Circle stage (2 sequential actions), and Square stage (3 sequential actions). The intervention consisted of 12 sessions, distributed over 4 weeks, with 3 sessions per week. Each session lasted 25 min

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TABLE 1 (*Continued*) Description of the studies.

Authors and year	Participants		Participants/ Groups		Aim	Adverse health condition	Description of the intervention
	n	*Age*	*CG*	*TG*			
Alsaif and Alsenany (2015)	40	6–10 years old	20	20	To determine the effects of interactive play with Nintendo Wii Fit games on motor performance	Spastic cerebral palsy	An intervention based on the Nintendo Wii Fit was used and conducted at home over a period of 12 weeks, with daily 20-min sessions, five times per week. Each child in the TG received a Nintendo Wii Fit console, which offered approximately 20 different games. Meanwhile the CG continued with conventional treatments only, serving as a basis for comparison of the outcomes
Chen et al. (2012)	30	6–12 years old	14	16	To investigate the effectiveness of a novel Virtual Home Cycle training program protocol in an RCT design to improve muscle strength and gross motor function	Spatic cerebral palsy	The format followed was 5 min to warm up + 20 min of exercise +5 min to cool down. The system used was the Eloton SimCycle Virtual Cycling System, this system consists of a cycling machine with a library of exercise videos to guide users through virtual exercise. The program was set for 40 min per day, 3 times per week for 12 weeks and the CG realized general physical activities at home
Chen et al. (2013)	27	6–12 years old	14	13	To investigate the effectiveness of a novel Virtual Home Cycle training program protocol to improve bone density	Cerebral palsy	The format followed was 5 min to warm up + 20 min of exercise + and 5 min to cool down. The system used was the Eloton SimCycle Virtual Cycling System, this system consists of a cycling machine with a library of exercise videos to guide users through virtual exercise. The intervention lasted 12 weeks, with a frequency of 3 days each week and each session lasted 40 min
Meyns et al. (2017)	3	8–10 years old	0	3	To analyze whether 6-week VR home training can promote balance control across a variety of clinical scales	Spatic cerebral palsy	This randomized clinical trial is investigating the effects of a home-based VR training program consisting of 30-min sessions, five times per week for 6 weeks, using Kinect sports games with a specific focus on balance development. Although the study is still in the early recruitment phase (only five children have been enrolled so far), preliminary data from three participants who completed both pre- and post-training assessments over the 6-week period are already being analyzed

Abbreviation list: CG, control group; TG, treatment group; VR, virtual reality; DCD, developmental coordination disorder.

TABLE 2 Description of the interventions of the included studies.

Authors and year	Outcomes	Assessed domains				Results
		Domains	Tool assessment			
Romano et al. (2022)	Manual dexterity was assessed using the 9HPT. Gait was measured using the T25FW, which records the time taken to walk 7.6 m	Finger dexterity	9HPT (Dominant hand)		ΔTG = 3 (3.9), ΔCG = −2.6 (3.1); p = 0.01	The protocol was able to improve manual dexterity in the TG; however, global mobility, as measured by walking performance on the T25FW, did not show any significant change in either group. The results suggest that the intervention was effective in improving hand function but did not have a substantial impact on gait or other aspects of ataxia
		Global mobility ability	T25FW		ΔTG = 0.1 (0.8), ΔCG = 0.3 (0.7), p = 0.31	
Ebrahimisani et al. (2020)	The aspects of predictive motor control analyzed were: a. Motor Imagery, assessed through the hand rotation task; b. Planning of anticipatory actions, assessed through the sword task; and c. Rapid online control, assessed through the rotary pursuit task	Motor imagery	Hand Rotation Task		TG = 1.56 (0.39), CG = 1.86 (0.47); p = 0.031	The VR intervention significantly improved motor imagery speed, action planning ability, and anticipatory motor control in the treatment group. The results suggest that VR may be a valuable tool for neuromotor rehabilitation in this population
		Action planning	Sword Task		TG = 16.1 (1.77), CG = 13.65 (1.75); p < 0.001	
		Rapid online control	Pursuit Rotatory Task (TOT, CCT, DP, DT)	TOT	TG = 10273.66 (2394.86), CG = 6037.44 (2244.03)	
				CCT	TG = 1798.38 (747.8), CG = 1,079.15 (416.3)	
				DP	TG = −4.62 (3.3), CG = −3.88 (7.2)	
				DT	TG = 9.71 (7.1), CG = 27.11 (15.1)	
Şahin et al. (2020)	Gross motor functions and fine motor functions were assessed using the BOTMP-SF, and independence in activities of daily living was evaluated using the WeeFIM.	Motor function	BOTMP-SF		TG = 34.5 (15.71), CG = 8.73 (19.77); p < 0.001	The intervention group showed significant improvements in overall motor function, gross motor skills, fine motor skills, and independence. The intervention demonstrated superior efficacy compared to conventional therapy and led to comprehensive improvements in motor abilities and independence
		Running speed and agility			TG = 1.03 (1.12), CG = 0.73 (1.55); p < 0.001	
		Balance			TG = 1.03 (1.18), CG = 1.03 (2.32); p < 0.001	
		Bilateral coordination			TG = 0.30 (0.65), CG = 0.80 (1.78); p = 0.751	
		Strength			TG = 1.63 (2.09), CG = 0.53 (1.16); p < 0.001	
		Upper-limb coordination			TG = 1.36 (2.96), CG = 0.90 (1.76); p = 0.052	
		Fine motor function			TG = 1.56 (3.14), CG = 0.96 (2.14); p = 0.095	
		Visualmotor			TG = 1.80 (3.10), CG = 3.2 (7.26); p = 0.17	

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TABLE 2 (*Continued*) Description of the interventions of the included studies.

Authors and year	Outcomes	Assessed domains			Results
		Domains	Tool assessment		
		Manual dexterity		TG = 1.00 (2.24), CG = 0.86 (2.06); p = 0.26	
		Gross motor function		TG = 15.13 (6.75), CG = 3.06 (6.83); p < 0.001	
		Fine motor function		TG = 17.80 (11.39), CG = 5.03 (11.36); p < 0.001	
		Locomotion	WeeFIM	TG = 1.86 (2.96), CG = 0.60 (2.04); p = 0.008	
Pourazar et al. (2018)	RT—888 Automatic Reaction Time Device was used to measure Reaction Time (SRT and DRT). The experiment was performed individually in a quiet room. They were instructed to perform reaction time tasks as quickly and accurately as possible	SRT	RT—888 Automatic Reaction Time Device	TG = 0.343 (0.156), CG = 0.576 (0.236); p = 0.018	The treatment group reduced both simple reaction time and discriminative reaction time, while the control group maintained their performance in both
		DRT		TG = 0.568 (0.177), CG = 0.884 (0.343); p = 0.018	
Lu et al. (2018)	The assessments included two main tests. The "Grid Game" (3 × 3) - The children were evaluated on two skills: first, following verbal instructions like "turn left" or "move straight" to navigate a toy across the grid. While in the "Do As You See" game, giving directions to guide the instructor to a candy within the same grid. The "Do As You See" test measured hand-eye coordination by requiring children to raise their right hand when seeing candy and wave their left hand when seeing a toy, with objects presented in different positions to ensure proper response	Direction-following	Grid Game	TG = 1–4 attempts, CG = 1–15 attempts; p = 0.036	The intervention proved effective in teaching how to follow and give instructions and improved hand-eye motor coordination. Additional improvements were reported in the development of social skills, as well as reinforcement of academic concepts such as shapes and numeracy
		Psychomotor skills		TG = 1–4 attempts, CG = 1–11 attempts; p = 0.036	
		Hand-eye coordination	Do as you see test	TG = 1–2 attempts, CG = 1–4 attempts; p = 0.036	
Alsaif and Alsenany (2015)	Motor skills were assessed, including manual dexterity, balance, and aiming/grasping abilities, using the MABC-2. In addition, subtest 5:6 of the BOTMP was used to evaluate upper limb coordination, and the 1MWT was employed to assess general aspects of motor function	mABC-2 total test score	mABC	TG = 44.1 (5.21), CG = 39.1 (5.16)	The intervention demonstrated effectiveness in improving overall motor function, with specific benefits in coordination and balance. The control group maintained their performance. Finally, the results suggest that the tool can complement traditional rehabilitation and reinforce the feasibility of home-based intervention
		Manual dexterity		TG = 17.3 (1.25), CG = 11.3 (2.42)	
		Aiming and catching		TG = 15.9 (3.18), CG = 13.1 (3.11)	
		Balance		TG = 16.1 (3.10), CG = 12.7 (3.74)	
		Upper-limb coordination	BOTMP	TG = 3.78 (0.39), CG = 3.12 (0.66)	
		General motor function	1MWT	TG = 98.8 (6.75), CG = 91.8 (6.82)	

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TABLE 2 (*Continued*) Description of the interventions of the included studies.

Authors and year	Outcomes	Assessed domains			Results
		Domains	Tool assessment		
Chen et al. (2012)	The BOTMP was used to evaluate motor function in children, and standard scores for four gross motor subtests and gross motor composite were used for comparison. For the measure does muscle strength, the knee extension and flexion torque generated during repeated extension-flexion were measured with an isokinetic dynamometer. It was tested angular velocity was set to 60°/s and 120°/s, and the range of motion was set to 70° starting with the knee flexed at 80° and ending in an extension at −10°	Running speed and agility	BOTMP	TG = 5.5 (6.2), CG = 2.5 (4.0); p = 0.722	Motor function did not show significant differences in the subscales for running speed, balance, bilateral coordination, and strength. However, the treatment group showed a higher overall motor function raw score. Regarding muscle strength, the treatment group showed significant improvements, while the control group achieved only minimal gains. The intervention was effective in improving muscle strength, particularly in the flexor muscles
		Balance		TG = 7.2 (10.0), CG = 3.6 (3.6); p = 0.147	
		Bilateral coordination		TG = 12.5 (5.8), CG = 11.1 (5.7); p = 0.825	
		Strength		TG = 9.0 (6.1), CG = 5.7 (4.2); p = 0.315	
		Gross motor function		TG = 34.2 (23.2), CG = 22.9 (12.4); p = 0.130	
		Concentric knee extension 60°	Muscle strength	TG = 1.63 (0.78), CG 1.35 (0.55); p = 0.045	
		Concentric knee extension 120°		TG = 1.42 (0.60), CG 1.04 (0.59); p = 0.008	
		Concentric knee flexion 60°		TG = 0.71 (0.40), CG = 0.48 (0.33); p = 0.028	
		Concentric knee flexion 120°		TG = 0.64 (0.37), CG = 0.39 (0.28); p = 0.003	
Chen et al. (2013)	Muscle strength was assessed using two methods. An isokinetic test with the Cybex NORM® dynamometer measured peak torque (Nm/kg) of the knee extensors and flexors in the most affected limb at a velocity of 90°/s. Abdominal endurance was evaluated using the curl-up test, which quantified the maximum number of correct repetitions performed in 1 minute. Gross motor function was assessed using the GMFM-66, which evaluates changes in motor function based on 66 items, with scores processed using the Gross Motor Ability Estimator	Motor function	GMFM	TG = 84.2 (11.7), CG = 81.0 (8.8); p = 0.303	The treatment and control groups did not show differences in motor function. However, regarding muscle strength, the treatment group showed significant increases in knee extensors and flexors, as well as in abdominal endurance. The intervention was effective in improving muscle strength
		Curl-up strenght	Curl-up test	TG = 13.4 (9.6), CG = 8.7 (8.8); p = 0.174	
		Knee extension	Cybex NORM® isokinetic dynamometer	TG = 49.0 (20.9), CG = 40.3 (21.3); p = 0.023	
		Knee flexion		TG = 21.3 (9.9), CG = 13.3 (7.1); p = 0.002	
Meyns et al. (2017)	To assess the outcomes, the researchers are using three validated clinical scales: the 14-item PBS, the 9-item balance subtest of the BOTMP-2, and the 15-item TCMS.	Balance in the context of everyday tasks	PBS	Preliminary results showed significant improvements in at least two of the three assessment scales used. Participant 1 showed a 5-point increase on the PBS and 11-point gain on the BOTMP-2 balance test. Participant 2 demonstrated a 5-point improvement on the BOTMP-2 and a 9-point gain on the TCMS. Participant 3 stood out with an 8-point improvement on the BOTMP-2 and a remarkable 17-point increase on the TCMS. These initial results suggest that VR training may be particularly effective in improving postural control and static balance in children with cerebral palsy	
		Static and dynamic balance	BOTMP-2		
		Postural control (static and dynamic)	TCMS		

Abbreviation list: CG, control group; TG, treatment group; VR, virtual reality; 9HPT, 9-Hole PTG, test; T25FW, timed 25-foot walk; BOTMP, Bruininks-Oseretsky test of motor proficiency; BOTMP-SF , Bruininks-Oseretsky test of Motor proficiency–Short form; BOTMP-2, Bruininks-Oseretsky test of motor proficiency, second edition; WeeFIM, WeeFunctional independence measure; SRT, simple reaction time; DRT, discriminative reaction time; mABC −2, movement assessment battery for children–second edition; 1MWT, 1-min walk test; GMFM-66, gross motor function measure; PBS, pediatric balance scale; TCMS, trunk control measurement scale.

A randomized clinical trial (Jha et al., 2021) compared the use of VR combined with traditional physiotherapy to traditional physiotherapy alone, evaluating 38 children with bilateral cerebral palsy in terms of gross motor performance, balance, and daily living activities. Overall, the intervention protocol consisted of 60-minute sessions, four times per week, over a 6-week period.

Similar to the findings of AlSaif and Alsenany (2015), the aforementioned authors did not identify significant improvements following the intervention, as measured by the Pediatric Balance Scale (PBS) (43.8 ± 6.1 in the intervention group and 40.2 ± 5.4 in the control group; $p = 0.06$), the Gross Motor Function Measure-88 (GMFM-88), which evaluates gross motor skills (88.9 ± 6.9 in the intervention group and 86.6 ± 5.1 in the control group; $p = 0.254$), or the WeeFIM instrument, which assesses functional independence (95.2 ± 12.9 in the intervention group and 89.5 ± 14.2 in the control group; $p = 0.201$).

Although VR is a promising tool, its use in individuals with cerebral palsy requires studies with greater methodological rigor and more detailed descriptions of the study population in order to better understand the differences based on the type of cerebral palsy and anatomical distribution.

Developmental coordination disorder

Developmental coordination disorder (DCD) is of idiopathic origin and is classified under the neurodevelopmental disorders section and the motor disorders subsection of the DSM-5. Its diagnosis is based on four criteria: (i) acquisition and execution of motor skills inconsistent with the individual's age; (ii) motor difficulties that significantly interfere with activities of daily living, academic or occupational performance, leisure, and play; (iii) no better explanation for the motor impairments, such as intellectual disability, visual impairment, or other neurological conditions affecting movement; and (iv) onset of symptoms during the early developmental period (Blank et al., 2019).

In the present review, only one study addressing DCD was included. It evaluated 40 children and aimed to assess the effect of a VR training program using the Xbox 360 and Kinect sensor on predictive motor control functions (EbrahimiSani et al., 2020). After 8 weeks, the authors observed that children in the intervention group improved in motor imagery ability (intervention group: 1.56 ± 0.39; control group: 1.86 ± 0.47; $p = 0.031$) and action planning (intervention group: 16.1 ± 1.77; control group: 2.65 ± 1.75; $p < 0.001$) compared to the control group.

A systematic review conducted by Mentiplay et al. (2019) also evaluated VR- or video game-based interventions in children with DCD, focusing on motor outcomes. Similarly to EbrahimiSani et al. (2020), they identified a range of positive motor changes, although not specifically in predictive functions. The review included 325 children with DCD, who showed improvements in strength, anaerobic performance, aerobic fitness, and both static and dynamic balance.

In contrast to these designs, another group of authors (Gonsalves et al., 2015). Aimed to identify movement pattern differences between children with DCD and typically developing children using a VR system. A total of 38 children were analyzed, and no significant differences were found in hand path distance during a virtual table tennis game. However, when wrist and elbow angles were analyzed during two specific game movements, children with DCD showed significantly greater wrist extension angles (95% CI = 22.6–47.0; $p < 0.001$) and greater maximum elbow flexion angles (95% CI = 7.4–37.1; $p = 0.04$) compared to typically developing peers.

Based on these findings, it can be concluded that VR systems go beyond rehabilitation and training purposes, enabling the identification of differences in motor execution and body skills between children with neuromotor disorders and those with typical development—highlighting the need to further explore virtual environments even in typically developing populations.

Autism spectrum disorder

Although this systematic review, through a rigorous study selection process, included only one study addressing autism spectrum disorder (ASD), virtual reality (VR) has played multiple roles in this condition, ranging from diagnostic support (Alcañiz et al., 2022; Robles et al., 2022) to interventions aimed at enhancing motor learning in children (Biffi et al., 2018). An open-label, randomized controlled trial (Chu et al., 2023) although not directly assessing neuromotor outcomes in children with ASD, compared a digital therapy based on an interactive video game with learning style profile training—an intervention designed as a comprehensive, multidimensional correction tool that aligns the core challenges of autism with diagnostic and treatment frameworks.

In this study, 78 children with a mean age of 5.02 ± 0.52 years were evaluated over 20 weeks and 40 sessions. The results showed that children with ASD who participated in the digital immersion program demonstrated better use of their bodies and objects compared to those who underwent only the learning style profile training (95% CI = 1.211; $p = 0.03$). Although these findings are not entirely aligned with the age range and specific neuromotor outcomes targeted by this review, they suggest a positive effect of VR on neuromotor abilities—an effect not observed in the study by Lu et al. (2018), which did not report significant changes.

Exergames and custom intervention

Studies involving the development of interventions based on virtual reality and gamification should consider fundamental concepts for their application, such as the characterizing goal and target user groups, respectively: the main objective of the game and the targeted audience, as proposed by Göbel and Maddison (2017). These authors argue that the commercial technology used to implement VR can belong to two distinct classifications: a) those focused on entertainment; and b) serious games, which are not designed for entertainment and usually have well-defined characterizing goals and target user groups.

Commercial technologies for entertainment are widely used in studies exploring VR systems in exergames in the field of pediatric health (Andrade et al., 2019; Comeras-Chueca et al., 2021; Hassan et al., 2022; Ramírez-Granizo et al., 2020; Singh et al., 2025). Although not originally designed for a specific health purpose, the results of interventions based on this type of technology show various benefits in the pediatric population. On the other hand, VR-based serious games have a methodologically more robust and specialized construction for each target audience in question.

In this review, only two studies fit the characteristics of serious games proposed by Göbel and Maddison (2017): the study by Romano et al. (2022), which reported an improvement in finger dexterity ($p = 0.01$) but not in global mobility ability in children with ataxia. Their intervention used the Niurion® Kit–P2R software, which has both a well-defined characterizing goal and target user group, in addition to specialized software and hardware; and the study by Lu et al. (2018), which investigated outcomes related to direction-following, psychomotor skills, and hand-eye coordination in children with Autism Spectrum Disorder. After the intervention using the Pink Dolphins Game, the children in the treatment group showed better performance in the aforementioned outcomes compared to those in the control group ($p = 0.036$). The Pink Dolphins Game, like the Niurion intervention, has clear features regarding characterizing goal and target user group, reinforcing its classification as a serious game.

Both studies used commercial VR technologies based on serious games that, although methodologically more robust in construction, are poorly explored in the literature. This raises the issue of limitations in comparing results, since, due to their limited exploration, no other study was found involving either of the two serious games. Thus, this weakens the external validity of the studies, does not provide a basis for comparison and discussion, and does not represent the robustness necessary to ensure data validity, making the reported benefits more fragile. Given this, the collective authors of this review emphasize the need to expand investigations into serious games aimed at children's health.

Therefore, it can be concluded that beyond its use for rehabilitation or training to recover motor function in children with neuromotor disorders, VR can also be applied to the development of movement assessment models and even serve as a diagnostic aid. In summary, VR systems, whether based on commercial video games or specifically designed health-focused software, appear to be promising tools for improving the quality of life, health status, and autonomy of these individuals. Nevertheless, to better understand the impact of these technologies on neuromotor outcomes in children and adolescents with neurodevelopmental disorders, further research is required.

Final considerations

According to this systematic review, motor skills may benefit from virtual reality-based interventions in children with neuromotor disorders, with the most consistent evidence found for children with cerebral palsy, particularly those with unilateral involvement. Motor domains such as manual dexterity, balance, motor coordination, and reaction time showed positive outcomes across various studies.

However, efficacy appears to vary depending on the specific disorder, the type and distribution of the condition, and the VR technology employed. The high heterogeneity of intervention protocols underscores the need for methodological standardization in studies to facilitate the comparison of results.

In particular, future research should prioritize the development and investigation of purpose-built serious games for specific conditions, which are currently underrepresented. These not only offer more tailored interventions but also have the potential to contribute to intervention standardization, thereby enabling better conclusions regarding the observed disorder. Additionally, the use of various assessment tools increases the risk of confounding bias, underscoring the need for standardization in measurement approaches.

Finally, it is important to recognize that VR's role extends beyond rehabilitation; it also shows promise as a sophisticated and potentially low-cost tool for motor assessment, providing valuable insights into movement patterns. The author collective emphasizes that more methodologically rigorous and better-targeted research is essential to fully understand the impact of these technologies on neuromotor outcomes.

Author contributions

ABS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. WB: Data curation, Methodology, Supervision, Visualization, Writing – review and editing. RS: Conceptualization, Data curation, Formal Analysis, Methodology, Supervision, Writing – review and editing. BMS: Funding acquisition, Project administration, Visualization, Writing – original draft, Writing – review and editing. APS: Investigation, Project administration, Resources, Software, Writing – review and editing. KS: Investigation, Resources, Software, Validation, Visualization, Writing – review and editing. JS: Data curation, Funding acquisition, Methodology, Project administration, Validation, Writing – review and editing. MyS: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. MrS: Project administration, Software, Supervision, Validation, Writing – review and editing. SL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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