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Title: Effects of Virtual Reality–Based Interventions on Balance and Motor Function in Children with Down Syndrome: A Systematic Review

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Abstract

Purpose: Children with Down syndrome (DS) frequently have poor postural control, hypotonia, and ligamentous laxity, which impairs motor function and balance. Rehabilitation using virtual reality (VR) has become popular as an alternative to traditional therapy. The impact of VR-based therapies on motor function and balance in children with Down syndrome was assessed in this systematic review.

Methods: A systematic search of PubMed, Cochrane Library (CENTRAL), and Scopus was conducted for randomized controlled trials and experimental interventional studies published between 2014 and 2024. Eligible studies involved children with DS receiving VR-based balance or motor training compared with conventional therapy or control conditions. Two reviewers independently conducted study screening, data extraction, and methodological quality assessment using the Cochrane Risk of Bias 2.0 tool. Due to clinical and methodological heterogeneity, meta-analysis was not performed.

Results: Seven interventional studies were included, comprising four randomized controlled trials, one quasi-experimental controlled study, one within-subject experimental study, and one experimental motor learning study comparing individuals with Down syndrome and typically developing controls. Most studies utilized non-immersive VR platforms such as Nintendo Wii–based systems and Xbox Kinect, while one study employed a head-mounted display system. Overall, VR-based interventions were associated with improvements in balance outcomes and selected motor measures. In several trials, the effects were comparable to those observed with conventional rehabilitation; however, the magnitude and consistency of effects varied across studies.

Conclusions: VR-based rehabilitation may be a promising and engaging adjunct for enhancing balance and motor function in children with Down syndrome. Although current evidence suggests it may be comparable to conventional therapy, further high-quality studies with standardized protocols are needed to establish optimal intervention parameters and long-term effects.

Keywords: Down syndrome; Virtual reality; Balance training; Motor function; Pediatric rehabilitation

Highlights

- VR-based interventions were generally associated with improvements in balance outcomes in children with Down syndrome.
- Improvements were observed in both static and dynamic balance across multiple assessment tools.
- VR training also showed benefits for gross motor function, coordination, and motor timing.
- Interactive and game-based VR platforms enhanced engagement and therapy participation.
- VR-based rehabilitation may serve as an effective adjunct to conventional physiotherapy in pediatric Down syndrome.

Plain Language Summary

Children with Down syndrome often experience difficulties with balance and motor control that can limit movement, play, and daily activities. While conventional physical therapy is beneficial, repetitive exercises may reduce engagement over time. Virtual reality (VR)–based therapy offers an interactive alternative by using game-like environments that encourage active movement. This review found that children with Down syndrome who participated in VR-based training showed improvements in balance, posture, and motor coordination. VR activities such as standing, stepping, reaching, and responding to visual cues allowed children to practice movement in a safe and motivating way. Overall, VR-based rehabilitation appears to be a promising complement to conventional therapy, helping children stay engaged, build movement confidence, and improve participation in daily activities.

INTRODUCTION

Trisomy 21, often known as Down syndrome (DS), is a genetic disorder caused by an extra partial or full copy of chromosome 21. With an estimated prevalence of 14.6 per 10,000 live births, DS is regarded as a serious public health issue [1,2]. People with Down syndrome (DS) have a wide range of symptoms that affect several body systems, especially the neurological, cardiovascular, and musculoskeletal systems [3]. Due to hypotonia, ligamentous laxity, decreased muscle strength, and poor neuromuscular coordination, children with DS frequently have delayed motor development [4–6]. These impairments contribute to inadequate postural control, balance deficits, and altered proprioceptive input, which may limit functional mobility and participation in daily activities [2,5]. Consequently, children with DS require targeted interventions to enhance motor performance, balance, and overall well-being [7,8].

The management of DS commonly involves structured physical exercise and physiotherapy programs aimed at improving strength, balance, and motor skills [9,10]. Although conventional rehabilitation approaches are effective, several limitations have been reported. Children with Down syndrome demonstrate reduced peak and submaximal exercise capacity, including lower VO_2peak and shorter time to exhaustion, which may limit tolerance to prolonged or repetitive rehabilitation sessions [11]. As a result, the effectiveness of traditional rehabilitation programs may be reduced, leading to suboptimal motor outcomes.

In recent years, VR-based rehabilitation has gained attention in clinical rehabilitation settings [12,13]. Virtual reality encompasses a spectrum of technologies that differ in the level of immersion and interaction. Non-immersive VR typically involves screen-based or console systems (e.g., Nintendo Wii, Xbox Kinect), whereas immersive VR utilizes head-mounted displays to create a fully enveloping virtual environment. Mixed or augmented reality integrates virtual elements into the real-world environment. These distinctions are important, as different levels of immersion may influence user experience, safety, and therapeutic outcomes [12]. In this review, both immersive and non-immersive VR systems were considered eligible if they were used as structured rehabilitation interventions targeting balance or motor function . By enabling users to perform task-oriented movements within immersive or non-immersive computer-generated settings, VR systems provide real-time multisensory feedback, adjustable task difficulty, and structured, repetitive practice in an engaging and motivating therapeutic context [14,15]. VR-based interventions have been increasingly applied in physical therapy and rehabilitation settings due to their potential to enhance motivation, engagement, and motor learning [16,17]. Previous studies have demonstrated that VR-assisted motor training may improve sensory integration, balance, motor coordination, and adaptive function, thereby supporting functional performance in daily life activities [18–20].

Despite the growing interest in VR-assisted rehabilitation, evidence regarding its effectiveness in children with Down syndrome (DS) remains limited and fragmented. Although previous systematic reviews have explored the use of VR-based interventions in individuals with DS, important gaps persist, particularly with respect to balance and motor outcomes in children. Existing studies are characterized by small sample sizes and substantial heterogeneity in VR platforms, ranging from non-immersive systems (e.g., screen-based or console-based VR) to more immersive technologies, resulting in wide variability in intervention protocols and outcome measures. Moreover, it remains uncertain whether VR-based rehabilitation offers benefits comparable to or greater than those of conventional physical therapy in improving balance and motor function in children with DS. Accordingly, this systematic review addresses the following PICO-based research question: In children and adolescents with Down syndrome, do virtual reality–based balance and/or motor training interventions, compared with conventional therapy or usual care, improve balance and motor function outcomes? The primary outcomes of interest were objective measures of balance performance, while secondary outcomes included gross motor function, coordination, and related motor abilities.

MATERIALS AND METHODS

Review strategy and study registration

The PRISMA reporting guidelines were followed in the design of this investigation, which was a systematic review. The International Prospective Register of Systematic Reviews (PROSPERO; CRD42025646764) received the review protocol in advance.

Search strategy and data sources

Three electronic databases, including PubMed, the Cochrane Library (CENTRAL), and Scopus, were used to conduct a comprehensive literature search. To ensure inclusion of relevant and up-to-date evidence, the search covered studies published between January 2014 and December 2024. Searches were initially conducted in January 2024 and updated in December 2024. Search terms were developed to reflect the population, intervention, and outcomes of interest, and included combinations of “Down syndrome” or “trisomy 21” with “virtual reality,” “virtual environment,” “VR,” “exergaming,” and related game-based terms (e.g., Wii, Kinect), as well as outcome-related terms such as “balance,” “postural control,” “motor function,” and “coordination.” Randomized controlled trials, clinical trials, and experimental interventional studies (including within-subject designs) were eligible for inclusion. In addition, reference lists of relevant articles were manually screened to identify additional studies. Database-specific search strategies were applied, and detailed search results are summarized in Table 2.

Table 2. Custom search strategy for each database

Database	Search strategy	Hits
PubMed	("Down Syndrome"[Mesh] OR "Down syndrome"[tiab] OR "trisomy 21"[tiab] OR "Trisomy 21"[tiab]) AND ("Virtual Reality"[Mesh] OR "virtual reality"[tiab] OR "virtual realit*"[tiab] OR "virtual environment*"[tiab] OR "immersive reality"[tiab] OR "mixed reality"[tiab] OR "augmented reality"[tiab] OR exergam*[tiab] OR "video gam*"[tiab] OR videogam*[tiab] OR "serious gam*"[tiab] OR gamification[tiab] OR gamified[tiab] OR "game-based"[tiab] OR "Nintendo Wii"[tiab] OR Wii[tiab] OR Kinect[tiab] OR "Xbox Kinect"[tiab])	43
Cochrane Library (CENTRAL)	#1 ("Down syndrome" OR "trisomy 21") #2 ("virtual reality" OR VR OR "virtual environment*" OR immersive OR "mixed reality" OR "augmented reality" OR videogame* OR "video game*" OR exergam* OR "serious game*" OR gamification OR "game-based" OR Wii OR Kinect OR Xbox OR Nintendo) #3 (balance OR postural OR gait OR mobility OR motor OR coordination) #4 #1 AND #2 AND #3	30
Scopus	TITLE-ABS-KEY("down syndrome" OR "trisomy 21") AND TITLE-ABS-KEY("virtual reality" OR "virtual environment" OR VR OR videogam* OR exergam* OR gamification OR Wii OR Kinect) AND PUBYEAR > 2013 AND PUBYEAR < 2025	116

Inclusion criteria and outcomes of interest

The Population, Intervention, Comparison, and Outcome (PICO) framework was applied as follows: (i) Population: children or adolescents diagnosed with DS; (ii) Intervention: balance and/or motor training using virtual reality (VR)–based technology; (iii) Comparison: conventional balance or motor training, alternative interventions, or control conditions; (iv) Outcomes: improvements in balance and motor function (Table 1). Studies were eligible for inclusion if they investigated balance and/or motor outcomes in children with DS, used randomized controlled trial, clinical trial, or experimental designs, and involved pediatric populations with DS. Studies were excluded if they: (i) were review or systematic review articles; (ii) did not involve VR-based interventions; or (iii) did not focus on children with DS.

Table 1. PICO framework

Population:	Children or adolescents with Down syndrome receiving VR-based balance or motor rehabilitation
Intervention:	Balance and/or motor rehabilitation using virtual reality (VR)–based technology
Comparison:	Conventional balance or motor training, alternative interventions, or control conditions
Outcome:	Improvements in balance and motor function

Selection of studies

Reference management software (Mendeley) was used to manage citations and eliminate duplicate records. Two reviewers (N.M. and Y.W.) independently screened titles and abstracts based on predefined PICO criteria and eligibility requirements. Irrelevant studies were excluded, with reasons documented. Any disagreements were resolved through discussion, and a third reviewer (A.Z.) was consulted when needed. Full-text articles of potentially eligible studies were then reviewed, and those not meeting the inclusion criteria were excluded with documented justification.

Data collection and extraction

One reviewer (N.M.) extracted the data, while another reviewer (Y.W.) independently verified it. Extracted information included author names, country of origin, year of publication, sample size, VR platforms and devices used, intervention characteristics, and outcome measures related to balance and motor function.

Quality assessment

The Cochrane Risk of Bias instrument, version 2, was used to assess the quality of the included studies (RoB 2) [21]. Five domains were examined, including bias related to the randomization process, deviations from the intended interventions, missing outcome data, outcome measurement, and selective reporting of results. An overall risk-of-bias judgment was assigned to each study based on these domains. Disagreements in the quality assessment were resolved through discussion until consensus was reached among the reviewers.

Data synthesis

A narrative synthesis was conducted to summarize the effectiveness of VR-based rehabilitation interventions for children with DS, with balance and motor function considered as primary outcomes. Additional outcomes were treated as secondary findings. Due to heterogeneity in study designs, VR platforms, intervention protocols, and outcome measures, quantitative synthesis and meta-analysis were not performed. Extracted data were organized according to the following categories: Author and country; Year of publication; Sample size; VR platform and devices; Balance outcomes; Motor function outcomes; Other reported outcomes beyond balance and motor function

Certainty of Evidence Assessment

The certainty of evidence for the primary and secondary outcomes was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach. Evidence from randomized controlled trials was initially considered high certainty and was downgraded based on the following domains: risk of bias, inconsistency, indirectness, imprecision, and publication bias. Certainty levels were categorized as high, moderate, low, or very low. A

Summary of Findings table was prepared for the primary outcome (balance) and secondary outcome (motor function).

RESULTS

Search strategy

A systematic search of electronic databases, including PubMed, the Cochrane Library (CENTRAL), and Scopus, identified a total of 189 records. Prior to screening, six duplicate records were removed. Consequently, 183 records were screened based on titles and abstracts. After title and abstract screening, 176 records were excluded due to irrelevance, including studies that did not involve children with Down syndrome, did not use VR-based interventions, or did not assess balance or motor-related outcomes. Seven full-text articles were retrieved and assessed for eligibility. All seven studies met the predefined inclusion criteria and were included in the qualitative synthesis. No reports were excluded after full-text assessment. The study selection process is illustrated in the PRISMA flow diagram (Figure 1).

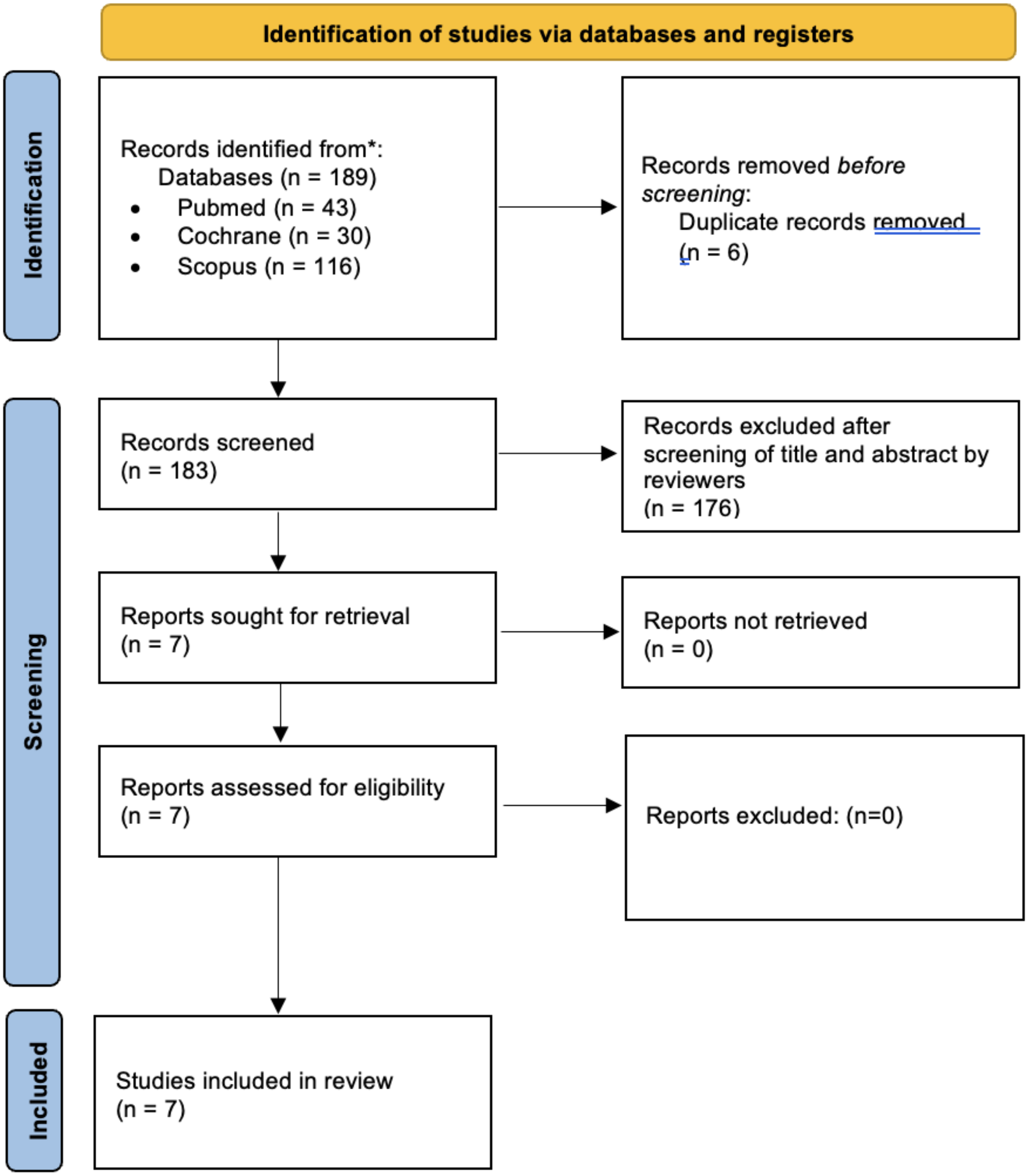

Fig. 1 Flow chart of the article selection process

Characteristics of included studies

The present systematic review included seven interventional studies published between 2014 and 2024. Four studies were randomized controlled trials comparing VR-based training with conventional therapy or control interventions [20,22–24]. One study used a quasi-experimental controlled design [25]. Two studies applied experimental designs without a traditional parallel control group, including a within-subject design [26] and a motor learning experimental task comparing individuals with Down syndrome and typically developing controls [27].

Balance outcomes were assessed in four studies using standardized clinical and functional balance tools, including the Pediatric Balance Scale (PBS), Romberg test, Timed Up and Go (TUG), and Five Times Sit-to-Stand Test (5xSTS) [20,22,23]. Postural control was also evaluated using center of pressure displacement measures in one study [24]. Motor-related outcomes were assessed in four studies, including gross motor development (TGMD-2), motor coordination (KTK), functional independence (ISS), and motor timing performance (coincidence timing task) [20,24,25,27]. Two studies reported improvements in both balance and motor-related outcomes [20,24].

Most studies utilized non-immersive VR platforms, particularly Nintendo® Wii-based systems (Wii Fit/Wii Sports) and Xbox® Kinect [20,22–24]. One study employed an immersive head-mounted display system (Oculus Quest) [26], while another used a custom-developed computer-based virtual task system developed at the University of São Paulo [27]. A detailed summary of study characteristics and outcomes is presented in Table 3.

Table 3. Characteristics and outcomes of VR-based training studies in children with Down syndrome						
Author, Country	**Year**	**Sample size**	**Type of training**	**Platform, devices**	**Outcomes measure & Main Results**	
					Motor function	**Balance**
Ghouri et al. [22], Pakistan	2024	24 (12 VR, 12 control)	- 30 min VR games (football, ski slalom, table tilt); trunk and lower-limb activities	Nintendo Wii & Wii Fit	Not directly assessed with a specific motor function scale	- Pediatric Balance Scale (PBS); Romberg test – Both groups improved; VR group showed greater improvement in static balance
Gaber et al. [25], Saudi Arabia	2024	18 participants (6 intervention, 6 traditional, 6 no intervention)	VR-based training program targeting independent skills (quasi-experimental)	Platform not specified	Independence Skills Scale (ISS) – Significant post-intervention improvement in VR group compared with control ($p < 0.001$). ISS post-test differences were significant across the three groups (χ^2=15.284, p<0.001), favoring the VR group.	Not assessed
Álvarez et al. [24], Chile	2018	16 participants	- 5 weeks, 2×/week (20 min/session); Wii-based game activities	- Nintendo Wii & Wii Balance Board	TGMD-2 – Significant improvement in gross motor development (manipulation subtest) in VR group	Center of pressure (posturography) –

		(9 intervention, 7 control)				Improvement in postural control after intervention
Reis et al. [20], Brazil	2017	12 participants (7 intervention, 5 control)	- 16 training session (20 minutes each), performed every 48 hours. - Game 1: "River rush": Drive small boat, collect items, side movement, jump. - Game 2: "Hall of ricochets": throw a ball, reach quick balls, move arms, legs, and head.	Xbox® 360 Kinect TM	Körperkoordinationstest für Kinder (KTK) – Significant improvement in motor coordination in VR group	- Pediatric Balance Scale (PBS) – Significant improvement in VR group compared with control
Ghafar et al. [23], Saudi Arabia	2017	26 participants (13 intervention, 13 control)	- 30 minutes VR Game: football, ski slalom, table tilt. Movement: strength of trunk, lower limb, and postural stability	Nintendo Wii Sports and Nintendo Wii Fit.	Not directly assessed with standardized motor development scale	- PBS on intervention group significantly improved (from 48.2 ± 4.6 to 57.75 ± 2.6) - Time up and go test on intervention group significantly improved

						(from 10.21 ± 2.0 to 7.01 ± 1.8) - The five times sit to stand on intervention group significantly improved (from 15.6 ± 2.6 to 11.2 ± 2.9) Intervention group significantly different with controlled group.
Monteiro et al. [27], Brazil	2017	40 Participants (20 DS, 20 non DS)	- 10 3D-cubes displayed simultaneously in a vertical column on a monitor. Participant press space bar on keyboard in the exact time to hit the object	3D image reproduces a coincidence timing task developed and tested by the Department of Electronic System Engineering of the Polytechnic School, University of São Paulo (EP/ USP) upgraded by the Laboratory of Information System from the University of São Paulo.	Individuals with DS who started with low performance improved coincidence-timing task with virtual objects (first block 714 ms, final block 359 ms), but were less accurate compared with non-DS individuals	Not assessed

Michalski et al. [26], Australia	2022	16 Participants	2 Drawing activities - Drawing in a VR application - Conventional drawing 24-hours washout period between activities	- Oculus quest (Facebook technologies, LLC) - Tilt brush, developed by google)	Behavioral outcomes (attention, mood, classroom behavior) improved after both interventions; no significant difference between VR and conventional	Not assessed

Abbreviations: NS: not specified; TGMD-2: test of gross development; PC CE: area of movement of the pressure center with eyes close; KTK: Körperkoordinatonstest Für Kinder; PBS: pediatric balance scale/Berg scale, VRTG: virtual reality therapy group; CG: control group; EO: eyes open, ISS: independence skills scale, ms: milliseconds); NS indicates that outcome measures were not explicitly reported in the original study.

Note: Although most included studies were randomized controlled trials, one study employed a within-subject experimental design without a separate control group. All included studies were interventional and reported balance- and/or motor-related outcomes relevant to the review objectives.

Quality assessment

The risk of bias of the included studies was evaluated using the Cochrane Risk of Bias tool version 2 (RoB 2) across five domains. Most studies were judged to have low risk of bias in domains related to deviations from intended interventions (D2), measurement of the outcome (D4), and selection of the reported result (D5). Regarding bias arising from the randomization process (D1), two studies were rated as having some concerns due to insufficient reporting of random sequence generation or allocation procedures [26,27]. In addition, two studies showed some concerns in the domain of missing outcome data (D3), primarily due to limited reporting of attrition or incomplete outcome data [25,27]. Based on the overall RoB 2 judgment, four studies were classified as low risk of bias [20,22–24], two studies had some concerns [25,26], and one study was rated as high risk of bias [27] due to concerns across multiple domains. A summary of the risk-of-bias assessment is presented in Figure 2.

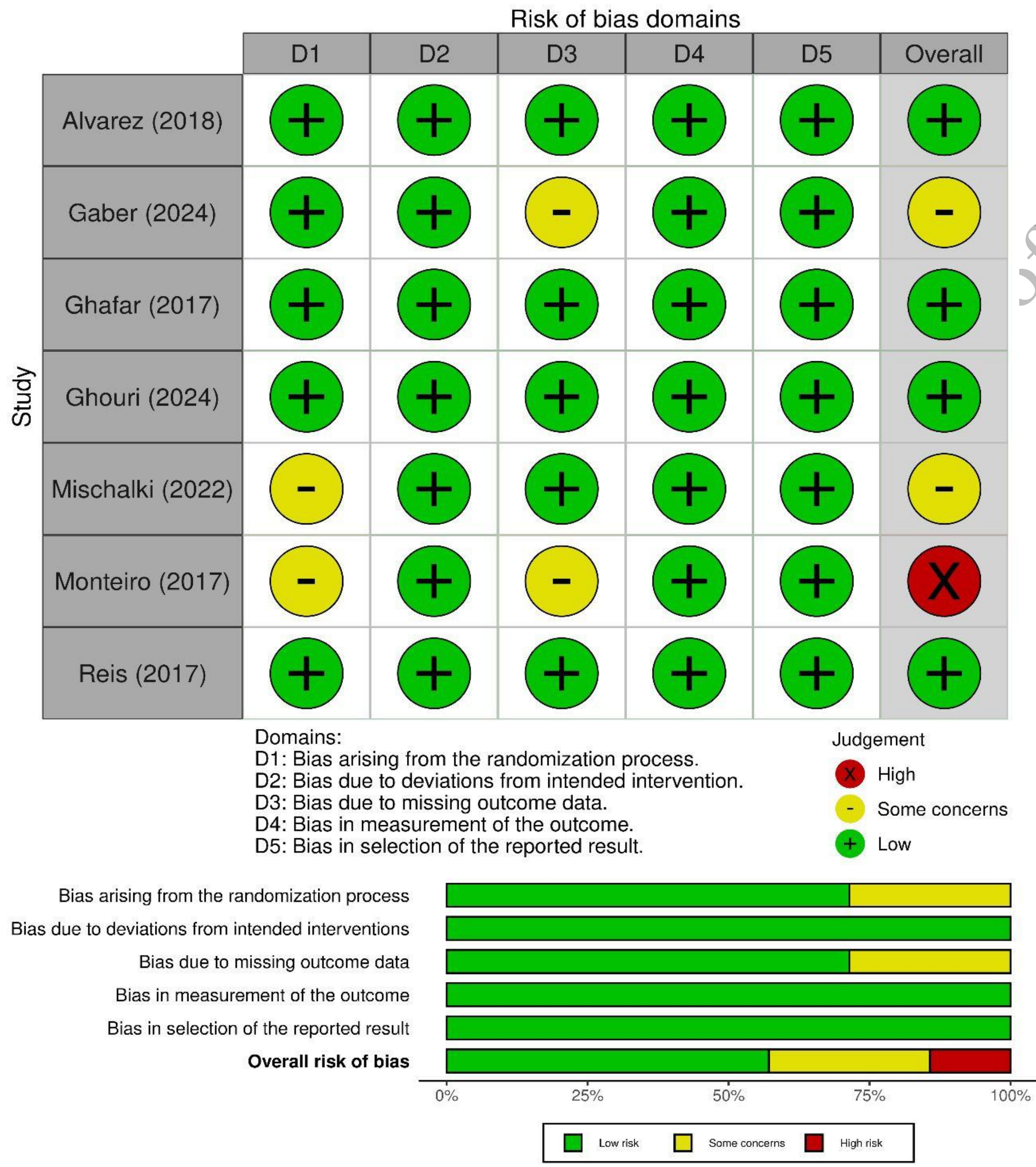

Fig. 2. Risk of Bias

Certainty of Evidence

According to the GRADE assessment (Table 4), the certainty of evidence for balance outcomes was rated as moderate. Although most included trials demonstrated low risk of bias and consistent direction of effect favoring VR-based interventions, the certainty was downgraded due to imprecision related to small sample sizes. The certainty of evidence for motor function outcomes was rated as low due to heterogeneity in intervention protocols and outcome measures, as well as limited sample sizes.

Table 4. Summary of Findings (GRADE**)**

Outcome	No. of studies (participants)	Direction of effect	Certainty of evidence (GRADE)	Reasons for downgrading
Balance outcomes (PBS, TUG, 5xSTS, KTK)	4 interventional studies (n=78)	Most studies favored VR compared with control	**Moderate**	Downgraded one level for imprecision (small sample sizes)
Motor function outcomes (TGMD-2, coordination, timing)	5 studies (n=102)	Mixed but generally favorable results	**Low**	Downgraded for imprecision and heterogeneity in outcome measures

Note: The number of participants contributing to each outcome reflects only those studies reporting the respective measures.

Summary of included studies

The included studies primarily evaluated the effectiveness of immersive or virtual reality–based interventions in improving balance and motor function in children with DS. Among the seven included studies, two reported improvements in both balance and motor function [20,24], four focused primarily on balance-related outcomes [22,23,25,27], and one evaluated motor-related outcomes without direct balance measures [26]. Across all included studies, a total of 152 participants were involved, including children with DS in both intervention and comparison groups, as well as non-DS controls in one study [27]. However, the number of participants contributing to each outcome varied depending on outcome availability across studies.

Balance outcomes were assessed in four studies using standardized clinical and functional balance tools. The balance assessment instruments included the Pediatric Balance Scale (PBS) [20,22,23], the Romberg test [22], the Timed Up and Go test (TUG) [23], and the Five Times Sit-to-Stand Test (5XSTS) [23]. Motor-related outcomes were evaluated using measures of gross motor development, coordination, and timing performance, including the Test of Gross Motor Development–Second Edition (TGMD-2) [24], the Körperkoordinationstest für Kinder (KTK) [20], and a coincidence timing task assessing motor timing and coordination [27]. A detailed summary of study characteristics, intervention protocols, and outcome measures is presented in Table 3.

Systematic review

Balance improvement

Balance outcomes were assessed in four of the seven included studies using a range of validated balance assessment tools. Owing to heterogeneity in outcome measures and intervention protocols, the findings were synthesized qualitatively. Three studies evaluated balance using the Pediatric Balance Scale (PBS) and reported significant improvements in balance performance after VR-based interventions compared with conventional therapy or control conditions ($p<0.05$) [20,22,23]. Improvements were observed in both static and dynamic balance components. In studies utilizing PBS, post-intervention gains were generally greater in the VR intervention groups, although improvements were also noted in control groups receiving conventional therapy.

Álvarez et al. evaluated postural balance using the Wii Balance Board, assessing center of pressure parameters with eyes open and eyes closed, and reported significant post-intervention improvements following VR training [24]. Similarly, Reis et al. reported significant improvements in balance-related tasks using the Körperkoordinationstest für Kinder (KTK), indicating enhanced motor coordination and balance control after VR-based therapy [20]. Additional balance-related improvements were reported using functional mobility tests, including the Timed Up and Go test and the Five Times Sit-to-Stand Test, with VR intervention groups demonstrating superior post-intervention performance compared with controls [23].

Motor function

Motor-related outcomes were evaluated in three included studies, primarily focusing on gross motor development, coordination, and motor timing. Álvarez et al. reported significant improvements in gross motor development following a VR-based intervention using Nintendo Wii games, as measured by the Test of Gross Motor Development–Second Edition (TGMD-2) [24]. Improvements were observed in locomotor and object control skills, alongside enhanced postural control. Reis et al. also demonstrated significant improvements in motor coordination and agility following VR-based training, with participants showing enhanced performance across multiple motor tasks after the intervention period [20].

Monteiro et al. examined motor timing and coordination using a coincidence timing task in individuals with DS and reported that participants with initially low performance demonstrated significant improvements in motor timing accuracy following VR-based task practice [27]. Although performance remained less accurate compared with non–DS controls, the findings suggest that VR-based motor training may support motor learning and coordination in children with DS. In contrast, Michalski et al. found no significant differences between VR-based and conventional drawing activities in terms of motor performance; however, both interventions were associated with improvements in attention, mood, and classroom behavior, indicating potential secondary benefits of VR engagement beyond motor outcomes [26].

DISCUSSION

The evidence from experimental and randomized studies examining the impact of virtual reality (VR)-based therapies on balance and motor function in children with Down syndrome (DS) was compiled in the current systematic review. Overall, the included studies suggest that VR-based rehabilitation may contribute to improvements in balance and selected motor outcomes in children with DS. However, the strength and consistency of these effects vary across studies.

Improvements in balance outcomes were consistently reported across the majority of included studies, particularly those utilizing standardized clinical balance measures such as the Pediatric Balance Scale, functional mobility tests, and instrumented postural assessments. These findings are in line with previous systematic reviews and experimental studies suggesting that VR-based interventions may enhance postural control and balance abilities in individuals with DS when combined with or compared to conventional physiotherapy approaches [18,28]. The interactive and task-oriented nature of VR environments may allow children to practice balance-related movements in a structured yet engaging context, potentially facilitating greater repetition and adherence compared with traditional therapy alone [13].

From a mechanistic perspective, VR-based balance training is proposed to enhance postural control by enriching multisensory feedback and facilitating the integration of visual, vestibular, and proprioceptive inputs, which are essential for sensorimotor coordination and balance regulation [29]. Real-time visual feedback, a core feature of many VR-based rehabilitation systems, may support error detection and movement correction, thereby facilitating motor learning and postural adaptation through feedback-driven sensorimotor recalibration [30]. This multisensory integration process is particularly relevant for children with DS, who often exhibit deficits in proprioception and neuromuscular coordination [2,5]. Furthermore, the graded difficulty and adaptive challenge embedded in many VR platforms may promote progressive loading of postural control systems while minimizing excessive physical or cognitive fatigue, thereby supporting sustained engagement during rehabilitation [31]. Consistent with these mechanisms, clinical evidence demonstrates that supervised VR-based training incorporating progressive task demands and interactive feedback results in significant improvements in objective postural control, functional mobility, and task-specific balance confidence, as reflected by reductions in center-of-pressure sway and gains in clinical balance outcomes [32]. Together, these findings suggest that VR-based rehabilitation integrates adaptive task design with feedback-driven motor learning processes, which may contribute to observed improvements in balance-related performance. However, given the variability in study design and sample size, these findings should be interpreted as preliminary rather than definitive evidence of effectiveness.

In addition to balance improvements, VR-based interventions demonstrated beneficial effects on motor function, particularly in gross motor development, coordination, and motor timing. Studies employing game-based VR systems such as the Nintendo Wii reported significant gains in locomotor skills, object control, and overall motor coordination [20,24] These improvements may be attributed to the combination of repetitive practice, task-specific training, and motivational engagement inherent to VR-based exercises, which are well-established contributors to motor learning in pediatric neurorehabilitation.

Evidence from systematic reviews and meta-analyses in children with cerebral palsy indicates that VR-based interventions consistently enhance gross motor function and balance, likely through repeated goal-directed movements, multisensory feedback, and play-based engagement that support sensorimotor adaptation and neuroplastic change [33,34]. In addition, the enriched multisensory input provided by VR systems, including real-time visual feedback and dynamic postural challenges, may further facilitate sensorimotor integration and postural control [30].

VR environments may also promote implicit motor learning by embedding therapeutic tasks within play-based activities, thereby reducing reliance on explicit verbal instruction and minimizing cognitive load [31]. This characteristic may be particularly advantageous for children with DS, who often present with limitations in attentional capacity, motor planning, and explicit learning strategies.

Motor timing and coordination outcomes, as demonstrated in the coincidence timing task study, further suggest that VR-based practice may support temporal aspects of motor control in children with DS [27]. Synchronizing movements with dynamic visual stimuli may promote sensorimotor coupling and feedforward postural control processes by requiring continuous prediction and adjustment of body position. Such mechanisms are often compromised in children with DS, who demonstrate delayed motor responses, altered center-of-pressure strategies, and inefficient anticipatory control during dynamic tasks [35]. Although motor performance in the present study did not reach the level of typically developing peers, the observed task-specific improvements suggest the occurrence of meaningful motor learning within the DS group.

Notably, not all included studies demonstrated the superiority of VR-based interventions over conventional approaches. One study reported no significant differences between VR-based and traditional activities in terms of motor performance, although both interventions were associated with improvements in attention, mood, and classroom behavior [26]. These findings suggest that, beyond motor outcomes, the benefits of VR-based rehabilitation may extend to psychosocial and behavioral domains that are clinically relevant for children with DS. Evidence from randomized trials and systematic reviews indicates that VR-based interventions can positively influence motivation, attention, learning behavior, mood regulation, and independence skills through engaging, game-based, and interactive therapeutic environments [36].

Enhanced motivation, enjoyment, and engagement during VR sessions may therefore contribute indirectly to improved therapy adherence and overall participation, even when direct motor gains are comparable to those achieved with conventional or balance-specific training approaches. This interpretation is supported by a double-blinded randomized controlled trial in children with cerebral palsy, which demonstrated that VR-based training was not consistently superior to balance-specific training in improving balance and gross motor function, yet was associated with high compliance, sustained participation, and positive user experience, supporting its role as a valuable adjunct rather than a replacement for conventional rehabilitation [37]. Complementary evidence from gamified VR exercise interventions further indicates that immersive and interactive virtual environments foster motivation, enjoyment, and psychological engagement, outcomes that are clinically meaningful and may reduce barriers to participation and promote inclusivity across diverse populations [38].

A major source of heterogeneity across studies relates to intervention dosage and platform characteristics. Intervention duration ranged from short-term programs of a few weeks to longer protocols, with variability in session frequency and intensity. Such differences make it difficult to determine an optimal therapeutic dose or to compare outcomes directly across studies. In addition, substantial variability existed in the type of VR platform used. Many studies employed non-immersive console-based systems (e.g., Nintendo Wii, Xbox Kinect), whereas fewer used head-mounted immersive systems. These platforms differ in sensory immersion and interaction style, and immersive environments may impose higher cognitive load, potentially affecting engagement, motor demands, and safety [39–43]. The limited number of immersive VR studies prevents meaningful comparison between immersion levels, and conclusions should therefore not be generalized across VR modalities.

Heterogeneity was also evident in the outcome measures used to assess balance and motor performance. Studies employed a range of clinical and functional measures, including the Pediatric Balance Scale (PBS), Timed Up and Go (TUG), Five Times Sit-to-Stand Test (5XSST), instrumented posturography, and coordination-based timing tasks. These tools assess related but distinct constructs (e.g., static balance, dynamic mobility, functional strength, anticipatory control), limiting direct comparability and preventing pooled quantitative analysis. Therefore, effect sizes could not be meaningfully aggregated, and conclusions rely on direction and consistency of findings rather than pooled magnitude estimates. Differences in measurement sensitivity and clinical thresholds further complicate interpretation of the magnitude of reported improvements.

Despite generally favorable findings, the overall certainty of evidence remains limited. Although most studies demonstrated low risk of bias, the small sample sizes and variability in VR platforms and outcome measures reduce confidence in the magnitude and generalizability of the observed effects. Therefore, the current evidence should be interpreted cautiously. There is currently no consensus regarding optimal VR intervention parameters, including intensity, frequency, duration, and level of immersion, all of which may influence therapeutic effectiveness. A recent scoping review highlighted marked heterogeneity across VR-based rehabilitation studies in relation to intervention dosage, platform characteristics, and outcome measures, underscoring the need for standardized protocols and clearer dosage guidelines to inform clinical practice [44]. Successful implementation of VR-based rehabilitation also requires adequate therapist expertise [45–47] in both clinical rehabilitation and technology use, as VR systems often necessitate individualized calibration, supervision, and monitoring to ensure safety and therapeutic appropriateness [48].

Potential publication bias should also be considered. Given the relatively small number of trials and the tendency for positive findings to be preferentially published, the overall effects reported in the literature may be overestimated [49,50]. In addition, the review included only studies published in English, which may have resulted in language bias [49] and the exclusion of relevant data from non-English publications. These factors may limit the comprehensiveness and external validity of the conclusions.

Future research should prioritize adequately powered randomized controlled trials with standardized intervention protocols and outcome measures. Comparative studies examining immersive versus non-immersive systems, as well as head-to-head comparisons with conventional therapy, are needed to clarify whether VR provides additive or equivalent benefits. Long-term follow-up studies are also required to determine the sustainability of motor and balance improvements and their translation into functional daily activities.

CONCLUSION

This systematic review indicates that virtual reality–based rehabilitation is a promising but still uncertain approach for improving balance and selected motor outcomes in children with Down syndrome. Although several randomized and experimental studies reported improvements in postural control and functional balance, the overall evidence base remains limited. The certainty of evidence ranged from moderate (for balance outcomes) to low (for motor outcomes), and substantial heterogeneity in intervention protocols, outcome measures, and VR platforms, together with small sample sizes, restricts definitive conclusions regarding clinical effectiveness. Therefore, while VR-based rehabilitation may represent a valuable adjunct to conventional therapy, higher-quality randomized controlled trials with larger samples, standardized outcome measures, and longer follow-up periods are needed to strengthen the evidence base and clarify its role in pediatric Down syndrome rehabilitation.

ETHICAL CONSIDERATION

Compliance with Ethical Guidelines

Formal ethical approval was not necessary for this systematic review because it was based on secondary analysis of published data and did not directly include human participants or identifiable personal information. The review methodology was carried out in compliance with PRISMA guidelines and the Declaration of Helsinki principles, and it was prospectively registered in PROSPERO (CRD42025646764).

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Author's Contributions

Conceptualization and methodology were contributed by N.M., I.Y., S.M.M.W., and N.R.R. Data curation and investigation were performed by N.M., Y.W., I.Y., S.M.M.W., and N.R.R. Formal analysis was conducted by N.M., Y.W., I.Y., N.R.R., and A.A.Z. Resources and software support were provided by N.R.R. Supervision was undertaken by S.M.M.W. and F.H. Validation and visualization were carried out by S.M.M.W. and A.A.Z. The original draft of the manuscript was prepared by N.M., while manuscript review and editing were performed by Y.W. and A.A.Z. All authors have read and approved the final version of the manuscript.

Conflict Of Interest

The authors declare that there are no conflicts of interest regarding the research, authorship, and/or publication of this article.

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