REVIEW ARTICLE

Virtual reality for enhancing athletic performance: A systematic review of evidence, mechanisms, and future directions

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ABSTRACT

This systematic review evaluates the effectiveness of Virtual Reality (VR) technology in enhancing athletic performance across physical, technical, and psychological domains, including injury rehabilitation contexts, through a comprehensive search of Scopus, PubMed, and Science Direct databases from inception to October 10, 2025, following PRISMA 2020 guidelines, which identified 793 articles, of which 7 experimental studies met the inclusion criteria after duplicate removal (n = 304), title and abstract screening (n = 489), and full-text eligibility assessment. The included studies demonstrated heterogeneous designs, samples, and outcome measures, yet consistently showed promising VR effects on physical performance outcomes (increased power output during HIIT by +5–19W, improved sprint and shuttle run performance), technical and motor skills (enhanced shooting performance, imagery skills, motor response time, and joint stability), and psychological outcomes (reduced cognitive and somatic anxiety, increased self-confidence, lower perceived pain, and higher enjoyment). However, methodological quality varied considerably, and the small number of studies, short intervention durations, and diverse sport contexts preclude strong generalizations, indicating that while VR is a promising supplementary training tool for controlled, psychologically demanding, and rehabilitation-focused environments, the field remains nascent, and this review provides a conceptual framework and structured research agenda to guide future investigations toward more rigorous, standardized, and ecologically valid studies.

Keywords: Virtual reality, Athletic performance, Sports training, Motor skills, Performance enhancement.

Cite this article as:
Febriyanti, I., Juniarisca, D. L., Wicahyani, S., Ridwan, M., Rizki, A. Z., & Ahmedov, F. (2026). Virtual reality for enhancing athletic performance: A systematic review of evidence, mechanisms, and future directions. *Journal of Human Sport and Exercise, 21*(4), 1336-1349. https://doi.org/10.55860/9nxkdr46

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Submitted for publication May 12, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/9nxkdr46

INTRODUCTION

In contemporary competitive sports, athletes face escalating demands for continuous performance optimization across physical, technical, and psychological domains (Bashir et al., 2022; Li & Smith, 2021). Soccer players, for instance, require high cardiorespiratory endurance, and interval training has demonstrated promise in enhancing this physical fitness component (Haleva & Meckel, 2020). Interval training has been shown to positively affect the cardiovascular system, improve aerobic capacity, and enhance overall physical performance (Franceschi et al., 2023; Oliveira et al., 2017; Panice et al., 2020). Physiological markers such as running economy, maximal oxygen uptake, and anaerobic threshold are typically used to assess aerobic fitness and guide training prescription (Strauss et al., 2014; Urquhart & Saynor, 2018). Notably, the anaerobic threshold has been identified as a particularly sensitive indicator of training effects, potentially outperforming maximal oxygen uptake in discerning performance variations among players of different competitive levels (Salvadori et al., 2021). Interval training regimens, characterized by short bursts of intensive activity interspersed with recovery intervals, have been shown to generate comparable or even greater physiological changes than moderate-intensity continuous training (Atakan et al., 2021; Collins et al., 2023; Liu et al., 2020; Tadiotto et al., 2023). The advantages of interval training are particularly pertinent for soccer players, whose demanding schedules often limit available training time (Krustrup & Bangsbo, 2015; Kunz et al., 2019).

In parallel with advances in training methodology, Virtual Reality (VR) technology has experienced rapid development and found wide applications across medical, educational, and entertainment domains (Fan et al., 2023; Kuna et al., 2023). However, one area that shows significant potential but remains relatively underexplored is its utility in improving sports performance. VR offers an innovative and interactive training method capable of simulating realistic competition conditions without injury risk (Ochi et al., 2022; Pastel et al., 2023). Additionally, VR provides a controlled training environment that can be tailored to individual athletes' needs a feature difficult to achieve through conventional methods (Radhakrishnan et al., 2023). In the context of performance enhancement, injury recovery, and mental preparation, VR represents a potentially transformative tool that opens new opportunities for coaches and athletes (Bui & Alaei, 2022; LeMarshall et al., 2023; Li Pira et al., 2023).

VR technology utilizes hardware and software to create immersive artificial environments. In sports contexts, devices such as headsets, motion sensors, and controllers generate three-dimensional simulations that respond to user movements and interactions in real-time (Loetscher et al., 2023). This technology enables athletes to perceive and react to situations resembling actual competition conditions without being physically present on the field or court. Furthermore, VR can integrate analytical data to provide detailed performance feedback, helping athletes identify improvement areas and formulate more effective training strategies (Doré et al., 2023). Applications also extend to mental training, where athletes can practice visualization and mental strategies in controlled environments, potentially enhancing mental endurance and focus during competition (Corrigan et al., 2023).

Despite growing interest, the evidence base for VR's effectiveness in sport performance enhancement remains fragmented and insufficiently synthesized. Previous literature has primarily focused on rehabilitation applications and basic skill acquisition (Aufegger et al., 2017; Choi et al., 2023), with limited systematic integration of findings across diverse performance domains. This fragmentation presents a significant gap, as practitioners and researchers lack a coherent framework for understanding how, for which outcomes, and under what conditions VR training is most effective (Akbaş et al., 2019).

Therefore, this systematic review aims to address this gap by synthesizing current evidence on VR effectiveness in enhancing athletic performance. Specifically, the review is guided by the following research questions: (1) What are the effects of VR-based interventions on physical performance outcomes in athletic populations? (2) What evidence exists for VR's effectiveness in improving technical and motor skills? (3) What are the psychological and perceptual outcomes associated with VR training? (4) What is the evidence for VR applications in injury rehabilitation contexts? (5) What are the current limitations and future research priorities for VR in sport performance enhancement?

METHODS

Study design

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). Due to the heterogeneity of included studies, quantitative meta-analysis was not feasible.

Search strategy

A comprehensive electronic search was conducted across three databases: Scopus, PubMed, and Science Direct. The search included studies published from database inception through October 10, 2025. Search terms were developed using Medical Subject Headings (MeSH) and free-text terms, combining concepts related to "*virtual reality*" and "*sport performance*." The detailed search strategies for each database are presented in Table 1. Search strategies were adapted iteratively to ensure sensitivity and specificity across databases. No manual reference screening was conducted to maintain systematic rigor.

Table 1. The detailed overview of the complete search strategy.

Database	Search term
Scopus	TITLE-ABS-KEY ("*virtual reality*" OR "*VR*") AND TITLE-ABS-KEY ("*sport performance*" OR "*athletic performance*" OR "*sports training*") AND PUBYEAR > 2015 AND (LIMIT-TO (DOCTYPE, "*ar*") OR LIMIT-TO (DOCTYPE, "*cp*")) AND (LIMIT-TO (LANGUAGE, "*English*"))
Pub Med	"*KEY*"("*virtual reality*"[MeSH Terms] OR ("*virtual*"[All Fields] AND "*reality*"[All Fields]) OR "*virtual reality*"[All Fields]) AND ("*athletic performance*"[MeSH Terms] OR ("*athletic*"[All Fields] AND "*performance*"[All Fields]) OR "*athletic performance*"[All Fields] OR ("*sport*"[All Fields] AND "*performance*"[All Fields]) OR "*sport performance*"[All Fields])
Science Direct	("*virtual reality*" OR VR) AND ("*sports performance*" OR "*athletic performance*" OR "*motor skill learning*")

Eligibility criteria

Studies were included if they met the following criteria: (1) original research investigating the effects of virtual reality on sports performance outcomes; (2) experimental or quasi-experimental study designs; (3) involved human athlete or physically active populations; (4) reported quantitative outcome data; (5) published in English; and (6) peer-reviewed journal articles.

Studies were excluded if they: (1) were review articles, conference proceedings, book chapters, or laboratory studies involving animals; (2) were duplicate publications; (3) lacked complete or adequate data for extraction; (4) were limited to abstracts or conference presentations only; or (5) focused solely on non-athletic populations or clinical rehabilitation without performance outcomes.

Study selection and screening process

Two independent reviewers (I.F. and D.L.J.) conducted the screening process. In the first stage, titles and abstracts of all identified records were screened against eligibility criteria. Potentially relevant records proceeded to full-text assessment. In the second stage, full texts were independently assessed for eligibility. Disagreements between reviewers were resolved through discussion and consensus, with a third reviewer (M.R.) available for arbitration when necessary. The screening process was documented and managed using Mendeley reference management software.

Data extraction

Data were systematically extracted from included studies using a standardized data extraction form. Extracted information included: author(s) and year, sample characteristics (size, age, sex, sport), study design, intervention details (VR modality, duration, frequency, intensity), outcome measures, and main findings. Data extraction was performed independently by two reviewers and verified for accuracy.

Quality and risk of bias assessment

Methodological quality and risk of bias of included studies were assessed using the Physiotherapy Evidence Database (PEDro) scale, which is appropriate for experimental studies in sports science (de Morton, 2009). The PEDro scale comprises 11 items evaluating internal validity, statistical reporting, and external validity. Studies were rated as "*excellent*" (9–10), "*good*" (6–8), "*fair*" (4–5), or "*poor*" (≤3) based on established criteria (Cashin & McAuley, 2020). Quality assessment was performed independently by two reviewers, with disagreements resolved through consensus.

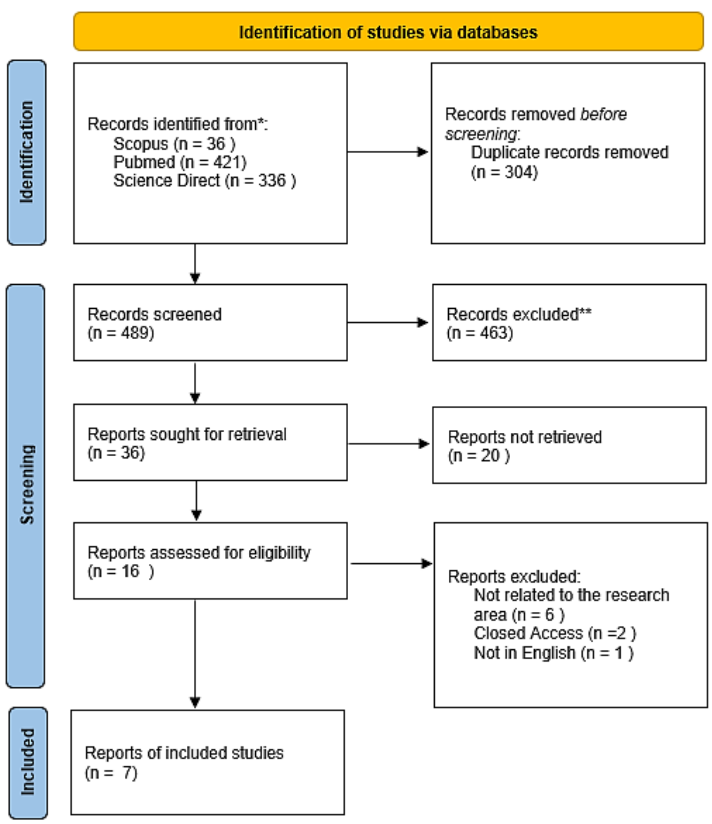

Figure 1. PRISMA 2020 flowchart of the article selection process.

RESULTS

Study selection

The systematic search identified 793 records from the three databases (Scopus: n = 36; PubMed: n = 421; Science Direct: n = 336). After removing duplicate records (n = 304), 489 articles remained for title and abstract screening. Following screening, 36 reports were sought for retrieval. Of these, 20 reports could not be retrieved. The remaining 16 reports underwent full-text eligibility assessment. At this stage, reports were excluded for the following reasons: not related to the research area (n = 6), closed access/unavailable (n = 2), not in English (n = 1). The final synthesis included 7 studies that met all inclusion criteria. The PRISMA flowchart illustrating the study selection process is presented in Figure 1.

Study characteristics

The seven included studies were all experimental designs, published between 2018 and 2022. Total sample sizes ranged from 13 to 45 participants (total across studies: N = 196). Participant populations included cyclists, football players, ice hockey players, wrestlers, and target-based sport athletes. Sample characteristics were predominantly young adults (mean age range: 20.5–21 years). Interventions varied considerably, including VR-HIIT exergaming, cycling with perceptual load manipulation, mixed-reality cycling competitions, VR motion analysis, VR training for injury rehabilitation, VR presence interventions, and VR-based imagery training. Intervention durations ranged from single sessions to 4-week programs. A summary of study characteristics is presented in Table 2.

Table 2. Summary of study characteristics, findings, and quality assessment.

Author (Year)	Sample characteristics	Study design	Intervention	Key results	PEDro Score (Quality)
Farrow et al. (2018)	16 (8 M, 8 F)	Experimental, cross-over	4 VR-HIIT conditions: blank, track, ghost, hard	Enjoyment higher for track vs. blank (diff: 0.9; 95% CI: 0.6–1.3). Mean power higher for track vs. ghost (+5 W) and hard vs. ghost (+19 W)	6/10 (Good)
Wender et al. (2022)	43 healthy (20 F, mean age 21)	Experimental, within-subjects	Cycling at "*hard*" intensity: no VR (NPL), VR low (LPL) & high (HPL) perceptual load	Significant main effects: condition ($F = 13.46$, $p < .001$) and time ($F = 113.05$, $p < .001$) on quadriceps pain	5/10 (Fair)
Westmattelmann et al. (2022)	Virtual Tour de France 2020 riders	Experimental	6 stages (hilly, high mountains, bumpy, etc.)	Relative power output explains most performance differences	4/10 (Fair)
Polikanova et al. (2022)	20 (13 hockey, 7 wrestlers)	Experimental	VR motion analysis: joint angles, stick speed, response time, hits/misses	Hockey players showed more stable joint patterns & fewer head movements (0.66 vs. 1.25, $p = .043$)	5/10 (Fair)
Nambi et al. (2020)	45 (15 per group)	Experimental, RCT	VR training (VRT) vs. IKT & control; outcomes: sprint, jump, shuttle run	VRT group improved pain, wellness, & sports performance vs. IKT & control	7/10 (Good)
Harrison et al. (2021)	13 female footballers (age 20.5 ± 1.1)	Experimental	VR presence questionnaire (spatial, involvement, realism)	Cognitive anxiety differed significantly ($\chi^2 = 18.63$, $p < .001$). VR vs. baseline ($p = .002$)	5/10 (Fair)
Bedir & Erhan (2021)	34 athletes	Experimental	VRBI training vs. VMBR+VM; shot performance & imagery skills	VRBI group showed greater improvement in shot performance & imagery over 4 weeks ($p < .05$)	6/10 (Good)

Physical performance outcomes

Farrow et al. (2018) investigated VR-HIIT exergaming in 16 participants (8 male, 8 female). The study compared four VR conditions (blank, track, ghost, and hard) during high-intensity interval training. Results demonstrated significantly higher enjoyment for the track condition compared to the blank condition (difference: 0.9; 95% CI: 0.6–1.3). Importantly, mean power output was higher for track compared to ghost (+5 W) and for hard compared to ghost (+19 W), suggesting that VR can enhance both affective responses and physical performance during HIIT.

Wender et al. (2022) examined VR-based distraction during cycling at "*hard*" intensity in 43 healthy young adults (20 female, mean age 21 years). The within-subjects design compared three conditions: no VR (NPL), VR with low perceptual load (LPL), and VR with high perceptual load (HPL). Significant main effects were found for condition ($F = 13.46$, $p < .001$) and time ($F = 113.05$, $p < .001$) on quadriceps pain. Notably, individuals cycling with immersive VR while performing a lower perceptual load task chose to exercise at higher intensity despite greater quadriceps pain. Conversely, those performing a higher perceptual load task did not increase training intensity but reported higher pain, possibly reflecting greater mental effort requirements.

Westmattelmann et al. (2022) analysed performance data from the Virtual Tour de France 2020 on the Zwift platform. The study identified that relative power output explained most performance differences across six stages. This research highlighted performance-outcome gaps that require consideration of competition strategy and equipment use, with important implications for emerging mixed-reality sports.

Nambi et al. (2020) conducted a three-arm randomized controlled trial involving 45 university football players (15 per group) with chronic low back pain. The VR training group demonstrated superior improvements in pain, wellness, and sports performance outcomes (40m sprint, 4×5m sprint, and shuttle run) compared to both isokinetic training and conventional exercise control groups.

Technical and motor skill outcomes

Polikanova et al. (2022) employed VR motion analysis to examine joint angles, stick speed, response time, and hits/misses in 20 athletes (13 hockey players, 7 wrestlers). Hockey players showed more stable joint patterns and fewer head movements compared to wrestlers (0.66 vs. 1.25, $p = .043$). The study demonstrated that VR can successfully train individual parameters necessary for high performance in hockey, including motor response time to puck arrival, stick response time, puck catching, and movement analysis.

Bedir & Erhan (2021) investigated VR-based imagery (VRBI) training compared to video-modelling with imagery (VMBR+VM) and control conditions in 34 athletes. The VRBI group showed significantly greater improvements in shot performance and imagery skills over 4 weeks ($p < .05$). The VRBI program demonstrated superior efficiency in terms of both shooting performance and imagination skills compared to the traditionally used VMBR+VM approach.

Psychological and perceptual outcomes

Harrison et al. (2021) assessed VR presence interventions in 13 female footballers (age 20.5 ± 1.1 years). Cognitive anxiety differed significantly across conditions ($\chi^2 = 18.63$, $p < .001$), with VR interventions showing significant reductions compared to baseline ($p = .002$). The VR intervention significantly reduced cognitive and somatic anxiety, increased self-confidence, and reduced heart rate. However, the authors noted that future research is needed to understand the relationship between VR relaxation, kinematics, and performance.

Overall evidence summary

Across the seven included studies, VR-based interventions demonstrated promising but heterogeneous effects across performance domains. The evidence suggests that VR may be particularly effective for: (a) enhancing enjoyment and motivation during high-intensity exercise; (b) improving specific technical parameters such as response time and joint stability; (c) reducing anxiety and increasing confidence; and (d) supporting rehabilitation outcomes. However, the small number of studies, limited sample sizes, short intervention durations, and diverse sport contexts preclude robust generalizations. Furthermore, the absence of long-term follow-up assessments and limited ecological validity represent significant gaps in the current evidence base.

DISCUSSION

Summary of main findings

This systematic review synthesized evidence from seven experimental studies investigating VR effectiveness for enhancing athletic performance across physical, technical, and psychological domains. The findings indicate that VR-based interventions show promise in improving several aspects of sports performance, including increased enjoyment and power output during HIIT (Farrow et al., 2018), enhanced motor response time and joint stability (Polikanova et al., 2022), improved shooting performance and imagery skills (Bedir & Erhan, 2021), reduced cognitive and somatic anxiety (Harrison et al., 2021), and better pain management and sports performance in athletes with chronic low back pain (Nambi et al., 2020). However, the evidence base remains limited, heterogeneous, and insufficient to support broad, context-independent conclusions about VR's efficacy across all sports and performance domains.

Interpretation of findings through theoretical lenses

The observed effects can be interpreted through established theoretical frameworks in motor learning and cognitive psychology. First, VR provides rich multisensory stimulation combining visual, auditory, and proprioceptive feedback that may accelerate motor learning and skill adaptation through enhanced neural plasticity (Juliano et al., 2022; Salvadori et al., 2021). This aligns with motor learning theory, which emphasizes the importance of varied, context-rich practice environments for robust skill acquisition (Schmidt & Lee, 2023).

Second, the immersive and realistic nature of VR supports cognitive theories of mental practice and imagery (Kweon et al., 2023; Le Franc et al., 2021). By simulating realistic game situations, VR enables athletes to experience high-pressure scenarios, potentially improving decision-making, focus, and performance under stress (Le Noury et al., 2022; Palidis et al., 2017). This aligns with the broader literature on simulation training across diverse domains (Aufegger et al., 2017).

Third, the observed improvements in psychological outcomes reduced anxiety, increased confidence, and enhanced enjoyment can be understood through attentional control theory (Eysenck et al., 2007). VR may serve as an attentional distraction, redirecting focus away from pain or anxiety toward task-relevant stimuli, thereby improving performance and reducing perceived exertion (Wender et al., 2022).

Conceptual framework for VR in athletic performance

Based on the synthesized evidence and theoretical interpretations, we propose a conceptual framework illustrating the pathways through which VR may influence athletic performance (Figure 2).

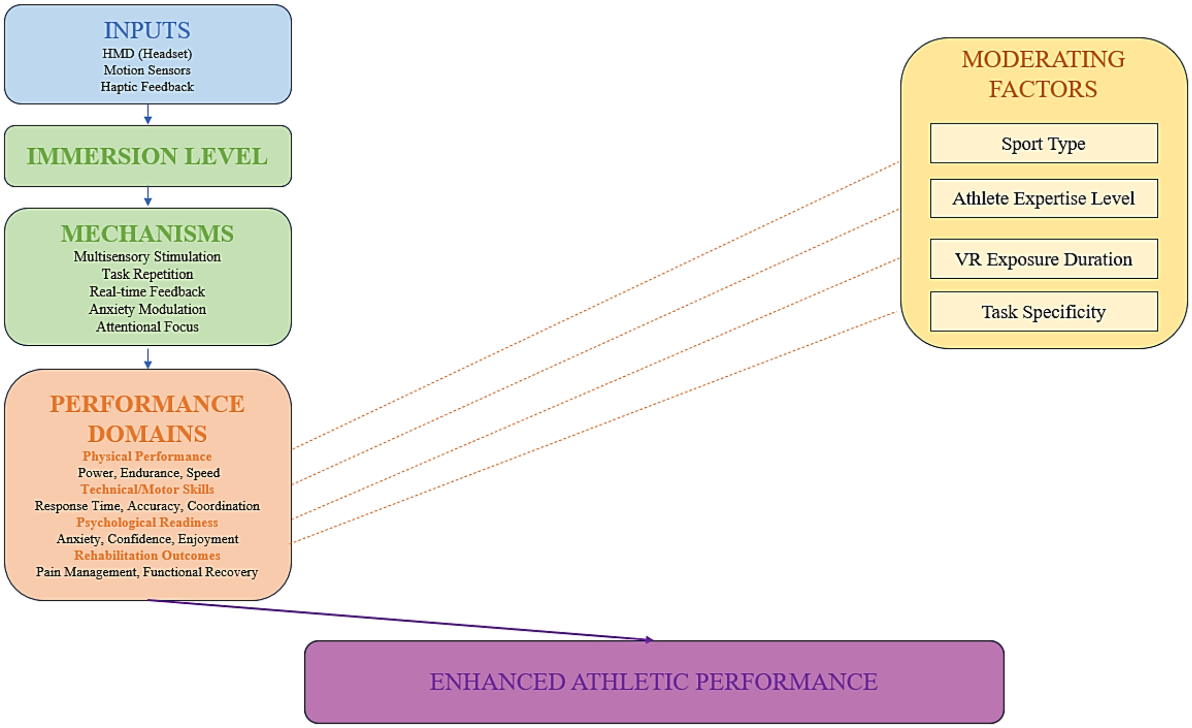

Figure 2. Conceptual framework: VR effect in athletic performance.

This framework positions VR as a multi-modal intervention operating through distinct yet interconnected pathways to influence performance outcomes.

Implications for theory and practice

The findings of this review have several implications for both theoretical development and practical application. For theory, this review underscores the importance of considering multisensory stimulation in motor learning research and highlights the need for integrative models that incorporate technological interventions into established performance frameworks. The conceptual framework proposed here offers a starting point for such integration, organizing the complex relationships between VR characteristics, mediating mechanisms, and performance outcomes. For practice, the findings suggest that VR can be a valuable supplementary training tool, particularly in contexts where: (a) physical training is limited by injury or logistical constraints; (b) psychological preparation is a priority; (c) specific technical parameters require isolated practice; and (d) performance monitoring and feedback are essential. Coaches and sports scientists should consider VR as part of a comprehensive training program rather than a replacement for traditional methods (Masiello et al., 2022). The personalized feedback and real-time monitoring capabilities of VR also present opportunities for individualized training prescription (Fusco & Tieri, 2022; Shah et al., 2023).

Social and ethical implications

The integration of VR into sports training raises several social and ethical considerations that warrant attention. Socially, the accessibility of this technology may be limited to athletes from developed countries or those with sufficient financial resources, potentially exacerbating existing performance inequalities (Arora et al., 2023). Ethically, it is important to ensure that VR does not replace the essential human interactions in training, such as emotional support and nuanced feedback from coaches (Arora et al., 2023). Additionally, the collection of personal data during VR training sessions raises privacy concerns that require appropriate safeguards. As VR adoption in sports expands, these social and ethical dimensions must be addressed proactively through policy development, equitable access initiatives, and ethical guidelines.

Contextualizing findings within the broader literature

The findings of this review align with emerging evidence across related fields. For instance, research on simulation training for musicians has demonstrated the value of mental practice and simulation for performance enhancement (Aufegger et al., 2017). Similarly, studies on VR rehabilitation have shown benefits for motor recovery in clinical populations (Choi et al., 2023). The application of VR to social skills training for autism spectrum disorders further illustrates the technology's versatility (Tan et al., 2022). Together, these diverse applications suggest that VR's potential extends beyond sport-specific outcomes to encompass broader human performance enhancement.

However, this review also reveals that the sport performance literature lags behind other domains in terms of methodological rigor, standardization, and evidence synthesis. While clinical and educational applications have benefited from established protocols, outcome measures, and quality standards, sport performance research remains fragmented, with considerable variability in study designs, VR modalities, and performance assessments.

Strengths and limitations

Strengths of this review include the systematic approach to literature search and selection following PRISMA guidelines, the inclusion of studies from multiple databases, and the application of quality assessment procedures. The narrative synthesis approach allowed for meaningful integration despite methodological heterogeneity.

Limitations include: (1) the small number of studies (n = 7) meeting inclusion criteria, limiting the generalizability of findings; (2) substantial heterogeneity in study designs, populations, interventions, and outcomes, precluding meta-analysis; (3) the lack of long-term follow-up assessments in included studies, limiting conclusions about sustained effects; (4) potential publication bias, as positive findings are more likely to be published; (5) limited representation of diverse sports populations, with most studies focusing on cycling, football, and hockey; and (6) the absence of formal assessment of ecological validity in the included studies. These limitations should be considered when interpreting the findings and planning future research.

Future research directions

Based on the findings and limitations of this review, we propose a structured research agenda to advance the field, emphasizing the need for future studies to move beyond generalized inquiries of VR effectiveness toward performance-specific trials that investigate which particular outcomes and under what conditions VR yields optimal benefits, requiring clearly defined and sport-specific measures. Long-term longitudinal studies with follow-up periods of at least six months are essential to establish the durability of VR training effects, including skill retention, transfer to real-world competition, and the sustainability of psychological benefits, thereby distinguishing between acute and lasting performance improvements. Furthermore, research must prioritize ecological validity by designing interventions that bridge the gap between virtual training environments and actual competition settings, addressing the critical gap in evidence regarding transferability. Concurrently, investigators should examine the social and ethical implications of VR adoption, including barriers to access, equity issues, data privacy concerns, and the development of ethical frameworks for informed consent and appropriate implementation. The field would also benefit from consensus on standardized outcome measures, protocols, and reporting guidelines specific to VR sport performance research to facilitate cross-study comparisons and meta-analytic syntheses. Finally, interdisciplinary collaboration among sports scientists, technologists, psychologists, and ethicists is imperative, as is systematic investigation of psychological and motivational factors such as individual differences in presence, immersion, and engagement that may moderate VR training effectiveness (Akbaş et al., 2019; Denche-Zamorano et al., 2023).

Research limitations

Several limitations of this review should be acknowledged. First, the sample of included studies may not represent the full population of athletes across various sports due to the limited number and diversity of studies. Second, the observed duration of VR use in training may have been too short to measure long-term impacts, as most studies employed brief interventions. Third, contextual factors such as individual psychological states, motivation, and prior experience with technology may influence outcomes but were not fully considered in the included studies. Fourth, the heterogeneity of outcome measures limited the ability to conduct quantitative synthesis. Finally, the quality assessment revealed methodological limitations in the included studies, suggesting that future research should prioritize rigorous experimental designs with appropriate controls, blinding, and sample size justification.

CONCLUSSION

This systematic review synthesizes the current, albeit limited, evidence on VR effectiveness for enhancing athletic performance across physical, technical, and psychological domains, indicating that VR shows promise as a supplementary training tool, particularly in controlled environments prioritizing multisensory stimulation, task repetition, and feedback, with demonstrated potential for improving power output, sprint performance, response time, joint stability, shooting accuracy, anxiety reduction, confidence enhancement, and enjoyment. However, the field remains nascent and the evidence base too heterogeneous to support broad generalizations, as the seven included studies exhibit considerable variability in design, intervention, and outcomes, while the absence of long-term follow-up and limited evidence for transfer to real competition represent critical gaps. This review provides a conceptual framework identifying three primary pathways motor skill enhancement, cognitive load modulation, and psychological readiness alongside a structured research agenda addressing performance-specific trials, longitudinal studies, ecological validity, equity and ethics, and outcome measurement standardization. Ultimately, realizing VR's potential as an essential component of modern sports training requires rigorous investigation, interdisciplinary collaboration, and careful attention to ethical and social implications to complement traditional methods and optimize athletic performance.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualization: Irma Febriyanti, Mochamad Ridwan, Ainun Zulfikar Rizki, Farruh Ahmedov. Methodology: Dwi Lorry Juniarisca, Sri Wicahyani, Mochamad Ridwan. Formal Analysis: Ainun Zulfikar Rizki, Farruh Ahmedov, Dwi Lorry Juniarisca. Investigation: Irma Febriyanti, Sri Wicahyani, Mochamad Ridwan. Data Curation: Dwi Lorry Juniarisca, Sri Wicahyani, Ainun Zulfikar Rizki. Writing – Original Draft: Irma Febriyanti, Ainun Zulfikar Rizki, Dwi Lorry Juniarisca. Writing – Review & Editing: Irma Febriyanti, Sri Wicahyani, Mochamad Ridwan, Farruh Ahmedov, Ainun Zulfikar Rizki. Supervision: Mochamad Ridwan, Farruh Ahmedov.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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