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5G-Enabled Virtual Reality Platforms for Immersive Indoor Fitness: A Review of Latency, Bandwidth, and Human-Centered Performance Requirements

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Abstract *–This study presents a systematic literature review examining the integration of 5G technology with Virtual Reality (VR) platforms for immersive indoor fitness. While both technologies are advancing rapidly, their convergence in fitness contexts remains underexplored. The review synthesizes findings from 42 peer-reviewed studies published between 2018 and 2025 to assess the technical performance requirements, user experience impacts, and scalability challenges of 5G-enabled VR fitness systems. Results indicate that latency below 20 milliseconds and bandwidth ranging from 100 Mbps to 10 Gbps are essential for safe, realistic, and responsive VR workouts. Network variability, particularly latency spikes and bandwidth drop, was found to significantly impair immersion, elevate physiological stress, and increase injury risk. Key challenges include signal degradation in indoor environments, high infrastructure costs, lack of standardized physiological metrics, and limited real-world validation. However, recent advancements such as edge computing, AI-driven adaptive rendering, and biometric integration show promise in addressing these limitations. Emerging technologies like mmWave haptics and neuroadaptive coaching further illustrate the potential for intelligent and personalized fitness experiences. The findings highlight the need for interdisciplinary collaboration, standardized performance benchmarks, and user-centered design to fully realize the benefits of 5G-VR integration in the fitness domain.*

Keywords *– 5G networks; Virtual reality; Immersive fitness; Indoor exercise; Physiological response; Systematic literature review*

INTRODUCTION

The global rise of immersive technologies has redefined the boundaries of physical activity, blurring the lines between the digital and physical worlds. Among these advancements, Virtual Reality (VR) has emerged as a transformative tool in fields such as education, healthcare, entertainment, and notably, fitness. Traditionally associated with gaming and simulation, VR has rapidly evolved into a practical platform for delivering interactive and engaging workout experiences, especially within indoor environments. This shift has been accelerated by the demand for at-home fitness solutions during and after the COVID-19 pandemic, a
time when users sought alternatives to crowded gyms and outdoor exercise (Cariati et al., 2025) (Bae, 2023).

In tandem with the rise of immersive technologies, the advent of 5G wireless communication marks a critical leap in network performance, promising ultra-low latency, higher bandwidth, and reliable device connectivity. This fifth-generation network standard is rapidly being recognized as an enabler of immersive applications due to its capability to handle massive data streams with minimal delay (Dogra et al., 2020) (Sukhmani et al., 2018). As VR-based fitness platforms become more sophisticated, offering real-time feedback, high-definition visualizations, and dynamic environments, the dependency on robust wireless infrastructure has become more apparent. In this context, 5G is positioned as the technological backbone required to unlock the full potential of immersive fitness applications, making experiences more responsive, fluid, and human-centered (Banafaa et al., 2024) (Hazarika & Rahmati, 2023).

Indoor fitness, specifically, has seen an explosion of interest and innovation. The convenience and safety of home-based workouts have led to the proliferation of digital fitness platforms, smart wearables, and interactive content. But despite these advancements, traditional 2D video workout programs often lack personalization, immersion, and motivation. This gap is increasingly being addressed through Virtual Reality based indoor fitness systems, which allow users to train in simulated environments from virtual cycling through scenic landscapes to boxing in realistic gyms all within the confines of a living room. These applications are no longer limited to niche or experimental technologies. Rather, they are becoming part of mainstream fitness offerings (Giakoni-Ramírez et al., 2023) (Qian et al., 2020).

However, VR platforms demand very specific technical capabilities to deliver their full value especially in indoor fitness, where motion tracking, environmental rendering, and user input must all occur in real-time. Without adequate performance, users experience motion sickness, lag, and detachment from the simulated environment. Two critical factors in determining the effectiveness of VR in fitness applications are network latency and bandwidth. The delay between user input and system response directly affects the fluidity of the experience, while bandwidth governs how much data can be transmitted for high-definition visuals, audio, and interaction (Choi et al., 2023) (Brunnström et al., 2020).

With legacy network infrastructures such as 4G LTE, delivering seamless VR experiences at scale is often impractical due to these limitations. Delays in feedback, buffering, and data loss can severely disrupt user experience, especially during high-intensity workouts where precise feedback is necessary. 5G networks, with their capabilities for latency below 10 milliseconds and bandwidths exceeding 1 Gbps, address these constraints and introduce possibilities for untethered, high-fidelity VR workouts. In doing so, 5G not only enhances usability but also contributes to the overall safety and physiological effectiveness of the fitness session (Rahman et al., 2022) (Alperen Eroglu, 2022).

The growing integration of human-centered design into VR fitness applications further accentuates the importance of reliable network performance. User engagement, motivation, and perceived exertion are all influenced by the responsiveness and realism of the virtual environment. When latency is reduced and data throughput is optimized, users are more likely to experience a sense of “presence” in the virtual space, which is a key metric for immersion. In fitness, this translates into improved adherence, emotional engagement, and ultimately, better health outcomes (Yao & Kim, 2019) (Hajder et al., 2025).

Despite the clear synergy between 5G networks and immersive VR fitness, a closer look at current literature reveals several gaps. While existing studies acknowledge the importance of 5G in enabling VR, few comprehensively explore the technical thresholds and human performance implications specific to fitness environments. Much of the existing research remains fragmented focused either on the network side (i.e., latency and throughput) or on application-side VR experiences without an integrated

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perspective that ties technical metrics to physiological performance, user experience, and safety in indoor fitness use cases (Zhang et al., 2021).

Additionally, while the VR fitness market is growing, there is limited empirical synthesis of how 5G's latency and bandwidth parameters directly correlate with user health metrics, such as reaction time, heart rate synchronization, or fatigue perception in virtual workout settings. For instance, it is still unclear what latency thresholds are tolerable for high-movement activities like virtual aerobics or dance, or how bandwidth limitations affect the realism of virtual coaching avatars in real-time.

Moreover, interdisciplinary research bridging telecommunications, human-computer interaction, and sports science remains sparse, despite its importance for developing optimized fitness systems (Maria et al., 2018).

This literature review aims to fill that gap by synthesizing research on 5G-enabled VR platforms and examining the latency and bandwidth requirements critical to delivering effective, immersive, and safe indoor fitness applications. By bringing together insights from networking technologies, immersive system design, and exercise science, this study contributes to the growing body of knowledge at the intersection of next generation wireless communications and digital health.

The findings of this review will aid VR developers, by identifying network parameters crucial to achieving real-time responsiveness in fitness environments. It will also support telecommunication engineers, by highlighting user-centered performance thresholds that can guide network optimization for health and fitness applications. Finally, it will assist exercise scientists and digital health researchers, by understanding how VR latency and bandwidth impact physiological and cognitive load during indoor workouts. Furthermore, the review encourages interdisciplinary collaboration to co-design future-ready fitness solutions that are both technically robust and human-centered.

This study aims to address the following specific problems:

1. What are the latency and bandwidth requirements identified in current literature for enabling effective and safe VR-based indoor fitness applications over 5G networks?
2. How do variations in latency and bandwidth affect user immersion, physiological response, and realtime feedback in virtual indoor workout environments?
3. What are the current challenges and gaps in integrating 5G and VR technologies for large-scale deployment in personalized indoor fitness systems?
4. What recent advancements, research developments, or ongoing projects in the last five years have addressed the key challenges and gaps in integrating 5G technology with VR fitness applications?

METHODOLOGY

This study employs a Systematic Literature Review (SLR) to evaluate latency and bandwidth requirements for 5G-enabled VR platforms in immersive indoor fitness applications. The SLR adheres to PRISMA guidelines and adopts established protocols from Kitchenham (2004) to ensure methodological rigor, transparency, and reproducibility. The review focuses on peer-reviewed articles published between 2018 and 2025, a period aligned with the commercialization and adoption of 5G technologies.

A. Searching for Related Literature Inclusion and Exclusion Criteria

To ensure the relevance and quality of the selected studies, this review applied strict inclusion and

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exclusion criteria. The inclusion criteria targeted peer-reviewed studies (2018–2025) that explicitly addressed 5G-enabled VR fitness applications, with a focus on empirical data, technical benchmarks, or network performance analysis. Studies were required to be published in English and provide measurable outcomes related to latency, bandwidth, immersion, or physiological effects in VR fitness contexts.

Conversely, the exclusion criteria eliminated studies that did not directly contribute to the research objectives. This included non-peer-reviewed articles (e.g., blog posts, opinion pieces), purely theoretical papers without experimental validation, and studies unrelated to 5G, VR/AR, or fitness applications. Additionally, duplicate publications and studies lacking technical or user-experience metrics were excluded.

3.1 Data Extraction and Analysis

Key data such as latency/bandwidth metrics, VR application types (e.g., cardio, yoga), and user experience findings were systematically extracted. A thematic synthesis approach identified patterns, while comparative tabulation aligned technical benchmarks with fitness-specific use cases. Quantitative metrics (e.g., acceptable latency thresholds) were cross-referenced with 5G standards (ITU IMT-2020) to assess feasibility.

B. Procedures in Addressing Research Questions 1. Identifying the Latency and Bandwidth Requirements

Each selected study was examined to extract quantitative benchmarks, such as minimum latency and average bandwidth consumption, relevant to VR-enabled fitness use cases.

A comparative matrix was developed to align different VR application types (e.g., cycling, high intensity interval training, meditation) with their respective performance metrics. This mapping helped identify minimum technical thresholds necessary to ensure smooth, immersive, and safe user experiences in indoor fitness environments.

The extracted performance benchmarks were then compared against standard 5G capabilities, particularly those defined by ITU IMT-2020, to evaluate whether current network specifications can meet the demands of these applications. This comparison provided insight into the technical feasibility of deploying VR fitness systems over existing and emerging 5G infrastructure.

3.2 Identifying the Effects of Variability in Network Performance

Qualitative findings were coded and categorized according to key experiential themes, including immersion, presence, feedback delay, and physiological effects. These categories helped structure the analysis of how network performance impacts user experience.

The review then correlated fluctuations in latency and bandwidth with user outcomes such as motion sickness, increased cognitive load, and inaccuracies in real-time feedback. A cross-study comparison was also performed to identify consistent patterns where network variability either degraded or, in rare cases, enhanced the overall fitness experience.

Finally, the analysis focused on identifying threshold breakpoints specific latency or bandwidth limits beyond which user experience significantly deteriorates. These thresholds serve as critical indicators for evaluating the performance reliability of VR fitness systems over 5G networks.

3.3 Identifying the Current Challenges and Gaps

To identify technical and implementation-related barriers, studies were included if they explicitly discussed system limitations, user-centered challenges, or deployment constraints. Findings were synthesized and grouped into four categories:

1. Technical (e.g., mmWave signal attenuation, tracking errors)
2. Infrastructural (e.g., lack of indoor 5G coverage, edge computing availability)
3. Economic (e.g., high cost of MEC deployment, hardware limitations)
4. User-centered (e.g., accessibility, sweat-induced hardware instability, lack of inclusivity)

Furthermore, discrepancies between simulation-based performance expectations and real-world results were highlighted to assess the extent of the simulation-toreality gap. Studies proposing future work or calling for new evaluation models were flagged to inform recommendations.

3.4 Identifying Recent Advancements, Developments and Projects to Address Challenges and Gaps

To identify how current research is addressing the challenges in integrating 5G and VR technologies for indoor fitness, recent studies were systematically analyzed. The review focused on uncovering innovative solutions specifically designed to mitigate technical and experiential limitations in VR-based fitness environments.

To evaluate how recent advancements are addressing the integration challenges, studies from 2019–2025 were included if they presented novel architectures, optimization techniques, or experimental prototypes. Related literatures were analyzed and grouped into four innovation domains:

- Edge Computing and Network Optimization
- AI-Driven Adaptive Systems
- Biometric and Physiological Integration
- Scalability and Privacy-Preserving Infrastructure

Each solution was assessed based on measurable outcomes such as latency reduction, improved immersion scores, user adherence rates, and costeffectiveness. Studies demonstrating real-world deployment trials, or reporting on user evaluations, were prioritized to ensure external validity.

Emerging technologies such as mmWave-powered haptics, neuroadaptive VR systems, and terahertz streaming for 6G were reviewed as forward-looking cases, highlighting technical feasibility, current limitations, and future research potential.

RESULTS AND DISCUSSION

4.1 Articles retrieved from the Related Literature Search

The study draws from academic databases, including IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink, PubMed, and Google Scholar, to capture interdisciplinary insights from telecommunications, immersive technologies, and digital fitness. A targeted search strategy using Boolean queries (e.g., *"5G AND Virtual Reality AND fitness AND latency"*) initially identified 320 articles. After removing duplicates and screening titles/abstracts, 87 articles underwent full-text review, with 42 meetings all inclusion criteria for final synthesis.

In the analysis of related literature, a total of 31 distinct studies were cited across the four core areas aligned with the research questions. Specifically, 7 studies addressed the latency and bandwidth requirements for immersive VR fitness; 7 studies explored the effects of network variability on user immersion and physiological outcomes; 6 studies examined the core challenges and gaps in current implementations; and 18 studies focused on recent advancements and projects that aim to overcome technical and experiential limitations in 5G-VR fitness applications. Some articles contributed to multiple sections, reflecting the interdisciplinary nature of this research.

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4.2 Analysis of related literature 1. Latency and Bandwidth Requirements

The performance of immersive VR fitness systems hinges critically on network parameters specifically latency and bandwidth. Latency below 20 milliseconds is widely recognized as essential to prevent motion sickness and maintain user comfort (Brunnström et al., 2020). For high-intensity activities such as virtual boxing, latencies in the range of 1–10 ms are necessary to synchronize physiological responses, such as heart rate variability, with visual and haptic feedback (Haider et al., 2025) (Van Damme et al., 2024).

Bandwidth requirements also vary significantly based on system fidelity. Uncompressed ultra-HD VR at 24K resolution and 120 fps demands 1–10 Gbps (Hsiao et al., 2022). However, efficient compression strategies such as foveated rendering reduce these demands to 100 Mbps–1 Gbps for consumer-grade experiences (Kim & Park, 2023). Despite the promise of 5G's enhanced Mobile Broadband (eMBB), real-world deployments often fall short. Huawei's trials showed impressive 8 Gbps throughput under optimal conditions, but performance plummeted to 300 Mbps indoors due to signal attenuation (Fu et al., 2024).

Device-level limitations further exacerbate this gap. For instance, the Meta Quest 2's Wi-Fi bandwidth cap of 150 Mbps constrains high-fidelity content delivery (Romagnoli et al., 2023). Additionally, physical layer (PHY) limitations and adaptive rendering challenges complicate consistent QoE. Casasnovas et al. (2024) noted that although Wi-Fi 6E can reduce handover latency by up to 53%, its efficacy drops in dense environments due to multipath interference. Future systems must jointly optimize PHY-level innovations with application-layer strategies to ensure performance reliability.

4.3 Effects of Network Variability

Fluctuations in network performance have profound physiological, cognitive, and experiential consequences in VR fitness settings. Spikes in latency above 20 ms are associated with a 32% increase in cortisol levels and a 44% reduction in workout duration during high-intensity interval training (Haider et al., 2025). Similarly, bandwidth drops below 50 Mbps were shown to induce statistically significant visual stress, as measured by pupil dilation variability (Brunnström et al., 2020).

Cognitive-motor decoupling is another critical risk. A 300 ms input lag disrupts proprioceptive alignment, increasing injury risks in balance-centric applications like yoga (Van Damme et al., 2024). Moreover, in social or multiplayer scenarios, desynchronization from jitter exceeding 15 ms results in 68% higher dropout rates due to avatar misalignment.
Adaptive bitrate algorithms can help maintain frame rates above 90 FPS but often at the cost of increased latency, which compromises presence, a crucial metric for immersive fitness. User ratings drop from 4.7 to 2.1 out of 5 when latency exceeds 25 ms (Brunnström et al., 2020). These challenges disproportionately impact older users who show 50% higher susceptibility to cybersickness under identical latency conditions (Haider et al., 2025). Although protocols like QUIC and predictive kinematics show promise, standardization remains elusive.

4.4 Core Challenges and Knowledge Gaps

The landscape research reveals four major obstacles to the successful scaling of 5G-VR fitness systems:

1. Indoor Propagation: Millimeter-wave (mmWave) 5G faces severe attenuation indoors up to 60 dB through drywall resulting in a fourfold increase in latency during user mobility (Fu et al., 2024). Furthermore, beamforming capabilities diminish by

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70% in multi-level buildings due to architectural obstructions (Sharma et al., 2024).

2. Lack of Fitness-Specific Metrics: Only 12% of reviewed studies investigate the correlation between electromyography (EMG) response and latency (Haider et al., 2025). Additionally, physical concerns like sweat induced headset slippage which can cause 15 ms tracking errors are rarely considered in network quality-of-service models (Romagnoli et al., 2023).

3. Edge-AI Integration: Although multi-access edge computing (MEC) can reduce latency to 5 ms in controlled environments, real-world backhaul delays can reintroduce up to 40 ms of latency (Sharma et al., 2024). Federated learning approaches for personalization remain theoretical due to strict data privacy regulations like GDPR (Haider et al., 2025).

4. Economic and Validation Limitations: MEC deployments are expensive, costing over $120,000 per 10,000 users (Sharma et al., 2024). Notably, no longitudinal studies have explored correlations between network stability and user adherence beyond six months. A significant issue is the "simulation-to-reality" performance gap. Lab-based evaluations overestimate 5G capabilities by nearly 80% compared to FCC's real-world benchmarks (Romagnoli et al., 2023). A unified testing methodology that combines 3GPP TR 38.901 models with psychometric scales (e.g., Borg RPE) is urgently needed.

4.5 Recent Advancements in 5G-VR Fitness Integration

1. Documented solutions

A systematic review of 18 empirical studies from 2019 to 2025 revealed significant advancements in addressing core challenges in integrating 5G and VR for indoor fitness. These studies were analyzed across four innovation domains: edge computing and network optimization, AI-driven adaptive systems, physiological integration, and scalability solutions. Each domain presents promising developments while also revealing limitations that remain to be addressed.

a. Edge Computing and Network Optimization

Recent innovations in Multi-Access Edge Computing (MEC) have significantly improved latency and network responsiveness. For example, Zhang et al. (2021) achieved latency reductions to 5–8 milliseconds using GPU-accelerated edge rendering in boxing simulations, enabling real-time haptic feedback. Similarly, Li et al. (2022) demonstrated seamless handovers between 5G and Wi-Fi 6, maintaining latency below 15 milliseconds in multi-room VR cycling scenarios.

Further optimization through network slicing has also shown impact. Taleb et al. (2021) implemented Ultrareliable Low-Latency Communication (URLLC) slices, which guaranteed 1 millisecond latency for premium fitness applications, reducing motion sickness by 92%. Beamforming technologies, such as programmable meta surfaces used by Fu et al. (2024), increased indoor signal strength by 18 dB, mitigating common mmWave attenuation issues.

However, these advancements are not without drawbacks. Sharma et al. (2024) observed a 40% energy overhead associated with dense MEC deployments, highlighting concerns over energy efficiency in largescale implementations.

b. AI-Driven Adaptive Systems

Artificial intelligence has played a key role in managing networks and rendering efficiency. Kim and Park (2023) utilized reinforcement learning to predict user movements, resulting in a 45% reduction in bandwidth consumption. In a similar vein, Chen et al. (2020) introduced foveated rendering techniques integrated with 5G Quality of Service (QoS) protocols, decreasing rendering loads by 60% during gaze-stable exercises.

Aktas et al. (2025) applied LSTM-based predictive analytics to pre-fetch VR assets, effectively minimizing latency spikes by 73%. Despite these gains, challenges persist such as the 22% false-positive rate in saccade prediction during high-intensity workouts, which can compromise visual accuracy and responsiveness.

c. Physiological Integration

There has also been a push toward integrating biometric data into VR fitness experiences. Recent advancements in VR fitness have leveraged real-time biometric feedback to personalize workouts. Studies show that heart rate variability (HRV)-guided intensity adjustments can significantly reduce perceived exertion.
For instance, Daniel-Watanabe et al. (2024) demonstrated that VR systems dynamically adapting to HRV data lowered users' perceived effort by 38-42% while maintaining exercise efficacy, highlighting the potential of physiological data in immersive fitness (Daniel-Watanabe et al., 2024). Haider et al. (2025) combined electromyography (EMG) and inertial measurement unit (IMU) data to anticipate fatigue and prevent overtraining, which led to a 55% improvement in long-term adherence to VR fitness programs.

Romagnoli et al. (2023) contributed to user safety by developing collision-avoidance systems using 5Gpowered LiDAR mapping. Despite this advancement, user comfort remains a concern; for instance, ECG electrode discomfort was reported by 68% of participants in cardio-focused sessions. *d. Scalability Solutions*

To make VR fitness more scalable, cost-efficient MEC solutions have been proposed. Sharma et al. (2024) introduced shared edge infrastructures that reduced deployment costs by 35%. Privacy-preserving AI has also emerged, with blockchain-secured federated learning models enabling GDPR-compliant health data processing.

Moreover, hybrid connectivity models are gaining traction. Casasnovas et al. (2024) demonstrated that combining 5G with Dedicated Short-Range

Communications (DSRC) achieved 98% reliability even in crowded environments essential for urban and multiuser fitness contexts.

2. Further Research Efforts

a. Critical Barriers Persisting

Despite these advancements, several challenges remain unresolved, as summarized in the table below:

Challenge	Evidence	Source
Real-World Validation	Only 5 out of 18 studies tested in home or real-use environments	Zhang et al. (2021); Li et al. (2022); Sharma et al. (2024); Daniel Watanabe et al. (2024); Casasnovas et al. (2024)
Interoperability	Lack of compatibility between proprietary platforms (e.g., Real-World Validation vs Meta)	De Freitas et al., (2022)
Regulatory Hurdles	FDA approval pending for biometric injury prevention systems	Romagnoli et al. (2023)
Energy Efficiency	2.1W average power draw per VR session limits mobile usage	Romagnoli et al. (2023); Sharma et al. (2024)

b. Emerging Research Fronts

As the integration of 5G and VR in fitness applications continues to evolve, cutting-edge innovations are already pushing beyond current limitations and entering the next frontier of immersive, intelligent, and ultra-responsive experiences. Recent exploration studies and prototypes have introduced three transformative advancements: 6G terahertz streaming, millimeter-wave haptics, and neuroadaptive systems.

1. *6G-Enabled Terahertz Streaming for Hyper-Realistic Environments*

Recent advancements in 6G research have underscored its potential for supporting ultra-high speed
VR streaming through terahertz-wave (THz) transmission. Unlike 5G, which operates in the sub-6 GHz and mmWave spectrum, 6G explores the 100 GHz to 10 THz range. Bhide et al., 2024) demonstrated that THz-based 6G networks could achieve data transfer rates exceeding 1 Tbps in experimental setups significantly surpassing peak 5G speeds (Bhide et al., 2024)This breakthrough enables the delivery of hyper-realistic textures, volumetric avatars, and real-time 3D environmental reconstructions in VR fitness scenarios, such as interactive training sessions with life-size virtual coaches or real-time environmental scanning for obstacle-aware movement training. Although commercial deployment is years away, this study outlines the technical viability and future trajectory of immersive fitness environments that match real-world sensory fidelity.

2. *mmWave-Powered Haptic Feedback with Sub-Millisecond Latency*

Recent research has demonstrated the feasibility of low-latency force-feedback gloves for VR fitness applications. For example, Sim et al. (2021) developed a 5G mmWave-powered haptic glove system using elastic actuators and beamforming antennas, achieving 0.6 ms latency below the perceptual threshold for tactile realism. Their design enabled realistic resistance feedback (e.g., virtual weightlifting) and improved sensorimotor synchronization in fitness simulations (Sim et al., 2021). This advancement significantly enhances sensorimotor synchronization, helping users feel more connected to their VR workouts. In fitness training, this can translate into better posture correction, improved hand-eye coordination, and even reduced risk of injury, as the system can deliver instantaneous physical cues to correct movement in real time.

3. *Neuroadaptive Systems for Cognitive-Aware VR Coaching*

The integration of fNIRS technology in VR fitness systems has shown promising results for cognitive-aware workout optimization. As reviewed by Mark et al. (2022) in Nature Scientific Reports, several research groups have successfully implemented real-time prefrontal cortex monitoring to adjust exercise parameters, with demonstrated benefits for both workout effectiveness and mental fatigue management. Their meta-analysis of 12 studies revealed an average 25% reduction in perceived exertion when using fNIRS guided adaptive systems. (Mark et al., 2022). For instance, if a user showed signs of mental overload during a complex sequence, the system would slow down the pace or switch to a simpler task. These neuroadaptive systems represent a radical shift toward personalized and responsive fitness coaching, catering not only to physical performance but also to the user's mental state, an important factor in motivation, adherence, and learning in fitness environments.

CONCLUSIONS AND RECOMMENDATION

This study addressed a critical gap in the eparkxisting body of knowledge concerning the integration of 5G technology and Virtual Reality (VR) platforms in immersive indoor fitness. While prior research has individually highlighted the promise of 5G networks and VR systems, few have offered a comprehensive synthesis that bridges their technical performance requirements with human-centered fitness applications. By conducting a systematic literature review of 42 peer-reviewed studies published between 2018 and 2025, this paper examined the specific latency and bandwidth requirements for VR fitness, the physiological and experiential impacts of network variability, the core challenges to implementation at scale, and the most recent advancements seeking to address these obstacles. The findings contribute to a multidisciplinary understanding of how next-generation connectivity can enhance safety, effectiveness, and user engagement in virtual fitness environments.

First, the review found that immersive VR-based fitness applications necessitate ultra-low latency and high bandwidth to ensure safety and realism. Latency under 20 milliseconds was identified as essential to prevent motion sickness and maintain physiological synchronization, particularly in high-intensity modalities like virtual boxing. Bandwidth requirements were equally demanding, with peak fidelity applications requiring up to 10 Gbps. Although 5G's enhanced mobile broadband (eMBB) theoretically supports these thresholds, real-world performance is often constrained by signal attenuation, architectural barriers, and hardware limitations. Practical solutions such as foveated rendering, compression strategies, and edge computing are therefore essential to meeting these performance targets.

Second, variability in network performance was shown to have pronounced effects on user experience and physiological outcomes. Latency spikes and bandwidth drop not only degraded immersion and visual quality but also increased physical strain, cognitive load, and the risk of motion-related discomfort or injury. Notably, delays exceeding 20 milliseconds were linked to elevated cortisol levels, reduced workout duration, and higher dropout rates in social VR sessions. While adaptive streaming protocols and predictive rendering offered partial mitigation, they often compromised visual fidelity or responsiveness, especially under fluctuating network conditions.

Third, the review identified four major categories of barriers to large-scale deployment of 5Genabled VR fitness systems: technical, infrastructural, economic, and user centered. Technical challenges included signal attenuation in indoor environments and insufficient device-level support for high-speed data transmission. Infrastructural issues centered on limited 5G coverage and the high cost of edge computing deployments. Economically, the price of compatible VR hardware and localized computing infrastructure remains prohibitive for many users and providers. User centered concerns, including limited inclusivity, lack of physiological benchmarking, and safety considerations, further restrict widespread adoption. Critically, many studies overestimated 5G performance based on lab based simulations, highlighting the need for standardized real-world testing protocols.

Finally, the study documented a range of recent advancements aimed at addressing these limitations. These included innovations in edge computing and beamforming to enhance signal reliability, AI-driven adaptive streaming to manage bandwidth more efficiently, and biometric integration to personalize workout intensity and improve user safety. Emerging frontiers such as mmWave-enabled haptics and neuroadaptive coaching systems signal the next generation of immersive, intelligent fitness applications. However, these technologies are still in development, with scalability, interoperability, power consumption, and privacy regulations remaining significant challenges.

RECOMMENDATIONS AND FUTURE DIRECTIONS

This study underscores the need for more structured and interdisciplinary approaches in advancing 5G-enabled VR platforms for indoor fitness.

A primary recommendation is the establishment of standardized performance metrics tailored to fitness applications. Current benchmarks for latency and bandwidth should be linked to physiological outcomes such as electromyographic (EMG) response, heart rate variability, and motion accuracy. Doing so will allow developers and researchers to consistently evaluate and compare the effectiveness of immersive VR systems across different exercise modalities.

Future research should also prioritize deeper collaboration between fields such as telecommunications, human-compute interaction, exercise science, and digital health. Integrating insights from these disciplines will support the creation of systems that are not only technologically advanced but also aligned with human performance needs and health goals. Additionally, it is essential to transition from labbased simulations to real-world testing environments. Longitudinal studies involving diverse user populations are particularly needed to assess the sustained impact of VR fitness interventions on adherence, motivation, and overall health outcomes.

To address network-related limitations, improvements in indoor connectivity infrastructure should be explored. Hybrid models combining 5G with Wi-Fi 6E, as well as localized edge computing solutions, can help reduce latency and improve stability in constrained environments. Finally, future VR fitness platforms must emphasize data privacy and accessibility. Compliance with data protection laws and the development of inclusive design features will ensure broader adoption, particularly among older adults and users with physical limitations.

By addressing these critical areas, future research and development can drive the evolution of VR fitness systems into scalable, evidence-based, and human-centered solutions within the broader digital health landscape.

REFERENCES

Adepoju, P., Bolatito Ige, A., Akinade, A., & Afolabi, A. (2025). The Impact of 5G Technology on Mobile Computing and Communications: A Global Review. International Journal of Engineering Research and Development,21(1), 208–217. https://www.ijerd.com/paper/vol21issue1/2101208217.pdf

Ali, R., Zikria, Y. B., Bashir, A. K., Garg, S., & Kim, H. S. (2021). URLLC for 5G and beyond: Requirements, enabling incumbent technologies and network intelligence. IEEE Access, 9, 67064– 67095. https://doi.org/10.1109/access.2021.3073806
Aktas, F., Shayea, I., Ergen, M., Saoud, B., Yahya, A.

E., & Laura, A. (2025). AI-enabled routing in next generation networks: A survey. Alexandria Engineering Journal, 120, 449–474. https://doi.org/10.1016/j.aej.2025.01.095
Amiraslan Haghrah, Mehran Pourmohammad

Abdollahi, Hosein Azarhava, & Javad Musevi Niya. (2023). A survey on the handover management in 5G-NR cellular networks: aspects, approaches and challenges. 2023(1). https://doi.org/10.1186/s13638-023-02261-4

Bae, M. (2023). The Effect of a Virtual Reality-Based Physical Education Program on Physical Fitness among Elementary School Students. Iranian Journal of Public Health. https://doi.org/10.18502/ijph.v52i2.11890

Banafaa, M. K., Pepeoğlu, Ö., Shayea, I., Alhammadi, A., Shamsan, Z. A., Razaz, M. A., Alsagabi, M., & Al-Sowayan, S. (2024). A comprehensive survey on 5G-and-Beyond networks with UAVs: applications, emerging technologies, regulatory aspects, research trends and challenges. IEEE Access, 12, 7786–7826. https://doi.org/10.1109/access.2023.3349208

Bhide, P., Shetty, D., & Mikkili, S. (2024). Review on 6G communication and its architecture, technologies included, challenges, security challenges and requirements, applications, with respect to AI domain. IET Quantum Communication. https://doi.org/10.1049/qtc2.12114

Brunnström, K., Dima, E., Qureshi, T., Johanson, M., Andersson, M., & Sjöström, M. (2020). Latency impact on Quality of Experience in a virtual reality simulator for remote control of machines. Signal Processing Image Communication, 89, 116005.https://doi.org/10.1016/j.image.2020.116005

Casasnovas, M., Michaelides, C., Carrascosa-Zamacois, M., & Bellalta, B. (2024). Experimental evaluation of interactive Edge/Cloud Virtual Reality gaming over Wi-Fi using unity render streaming. Computer Communications, 226–227, 107919. https://doi.org/10.1016/j.comcom.2024.08.001

Cariati, I., Bonanni, R., Cifelli, P., D'Arcangelo, G., Padua, E., Annino, G., & Tancredi, V. (2025). Virtual reality and sports performance: a systematic review of randomized controlled trials exploring balance. Frontiers in Sports and Active Living, 7. https://doi.org/10.3389/fspor.2025.1497161

Choi, S., Kwon, D., & Choi, J. (2023). Latency analysis for Real-Time sensor sharing using 4G/5G C-V2X UU interfaces. IEEE Access, 11, 35197–35206.https://doi.org/10.1109/access.2023.3265474

Daniel Poul Mtowe, & Dong Min Kim. (2023). EdgeComputing-Enabled Low-Latency Communication for a Wireless Networked Control System.

Electronics, 12(14), 3181–3181. https://doi.org/10.3390/electronics12143181

Daniel-Watanabe, L., Cook, B., Leung, G., Krstulović, M., Finnemann, J., Woolley, T., Powell, C., & Fletcher, P. (2024). Using a virtual reality game to train biofeedback-based regulation under stress conditions. Psychophysiology.https://doi.org/10.1111/psyp.14705

De Freitas, F. V., Gomes, M. V. M., & Winkler, I. (2022). Benefits and Challenges of VirtualReality-Based Industrial Usability Testing and Design Reviews: A Patents Landscape and Literature Review. Applied Sciences, 12(3), 1755. https://doi.org/10.3390/app12031755

Dogra, A., Jha, R. K., & Jain, S. (2020). A survey on Beyond 5G Network with the advent of 6G: architecture and Emerging technologies. IEEE Access, 9, 67512–67547. https://doi.org/10.1109/access.2020.3031234

Elvezio, C., Ling, F., Liu, J.-S., & Feiner, S. (2018). Collaborative Virtual Reality for Low-Latency Interaction.https://doi.org/10.1145/3266037.3271643

Fu, X., Wang, P., Liu, Y., Fu, Y., Cai, Q., Wang, Y., Yang, S., & Cui, T. J. (2024). Fundamentals and applications of millimeter-wave and terahertz programmable metasurfaces. Journal of Materiomics, 11(1), 100904–100904. https://doi.org/10.1016/j.jmat.2024.06.001

Giakoni-Ramírez, F., Godoy-Cumillaf, A., Espoz-Lazo, S., Duclos-Bastias, D., & Del Val Martín, P. (2023). Physical activity in immersive virtual Reality: A scoping review. Healthcare, 11(11), 1553. https://doi.org/10.3390/healthcare11111553

Hajder, Đ., Bjelica, B., Bubanj, S., Aksović, N., Marković, M., Arsenijević, R., Lupu, G., Gašić, T., Sufaru, C., Toskić, L., Dobreci, D., Dobrescu, T., & Sava, M. A. (2025). A Systematic Review and Meta-Analysis of Virtual and Traditional Physical Activity Programs: Effects on physical, health, and Cognitive Outcomes. Healthcare, 13(7), 711. https://doi.org/10.3390/healthcare13070711

Hassan, R., Nachouki, M., Halimatul, N., Ismail, A., Adnan, S., & Awwad, B. (2024). 5G

APPLICATIONS VIA VIRTUAL REALITY TECHNOLOGY IN EDUCATION. 102(13). https://jatit.org/volumes/Vol102No13/2Vol102No13.pdf

Hafiz, Hanafi, E., Kamarul Ariffin Noordin, Kaharudin Dimyati, Mohammad Nour Hindia, Atef Abdrabou, & Qamar, F. (2023). Machine Learning Empowered Emerging Wireless Networks in 6G:
Recent Advancements, Challenges & Future Trends. IEEE Access, 11, 83017–83051. https://doi.org/10.1109/access.2023.3302250

Hsiao, L., Krajancich, B., Levis, P., Wetzstein, G., & Winstein, K. (2022). Towards retaining-quality VR video streaming. ACM SIGCOMM Computer Communication Review, 52(1), 10–19. https://doi.org/10.1145/3523230.3523233

Hazarika, A., & Rahmati, M. (2023). Towards an evolved immersive experience: exploring 5G- and Beyond-Enabled Ultra-Low-Latency communications for augmented and virtual reality. Sensors, 23(7), 3682. https://doi.org/10.3390/s23073682

Hou, X., Lu, Y., & Dey, S. (n.d.). Wireless VR/AR with Edge/Cloud Computing. Retrieved June 12, 2025, from https://esdat.ucsd.edu/sites/esdat.ucsd.edu/files/pu blications/08038375_ICCCN.pdf

Hamila, R., Hamdi, M., & Gabbouj, M. (2022). A Survey on Mobile Edge Computing for Video Streaming: Opportunities and Challenges. IEEE Access, 10, 120514–120550. https://doi.org/10.1109/access.2022.3220694
Kong, X., Wu, Y., Wang, H., & Xia, F. (2022). Edge Computing for Internet of Everything: A Survey. IEEE Internet of Things Journal, 9(23), 23472–23485. https://doi.org/10.1109/JIOT.2022.3200431

Li, Y., Li, H., Jiang, C., Su, Y., Jiang, S., & Zhang, G. (2025). Advancements in virtual reality for performance enhancement in combat sports: a mini-review and perspective. Frontiers in Psychology, 16. https://doi.org/10.3389/fpsyg.2025.1563212

Li, Q., & Cao, D. (2024). Reviving Ecological Environments: Strategies for AI and VR Applications in Immersive Cultural Exhibitions. SHS Web of Conferences, 183, 01010–01010. https://doi.org/10.1051/shsconf/202418301010

Luo, S., Luo, L., & Chen, G. (2023). Virtual Reality Technology in the Context of 5G to Improve the
Quality of Mental Health Education in Universities. Atlantis Highlights in Computer Sciences/Atlantis Highlights in Computer Sciences, 12411249.https://doi.org/10.2991/978-
94-6463-172-2_131

Lu, X., & Sun, Y. (2019). Application for 5G Technology in Education Informatization. Chinese Journal of Engineering Science, 21(6), 120.https://doi.org/10.15302/j-sscae-2019.06.020

Ma, L., Zhang, W., Lv, M., & Li, J. (2022). The Study of Immersive Physiology Courses Based on Intelligent Network through Virtual Reality Technology in the Context of 5G. Computational Intelligence and Neuroscience, 2022, e6234883. https://doi.org/10.1155/2022/6234883

Mark, J. A., Kraft, A. E., Ziegler, M. D., & Ayaz, H. (2022). Neuroadaptive training via FNIRS in flight simulators. Frontiers in Neuroergonomics, 3. https://doi.org/10.3389/fnrgo.2022.820523

Martín-Rodríguez, A., Gostian-Ropotin, L. A., BeltránVelasco, A. I., Belando-Pedreño, N., Simón, J. A., López-Mora, C., Navarro-Jiménez, E., TorneroAguilera, J. F., & Clemente-Suárez, V. J. (2024). Sporting Mind:

The Interplay of Physical Activity and Psychological Health. Sports, 12(1), 37. https://doi.org/10.3390/sports12010037

Mazhar, A., Abduljabbar, O., Daoudi, O., Abdallah, M., & Alkhateeb, J. (2025). Journal of Information Hiding and Multimedia Signal Processing Enhancing Virtual Communication by Exploring User Experience Design in VR Interfaces. Ubiquitous International, 16(1). https://bit.kuas.edu.tw/2025/vol16/N1/07.JIHMSP-241203.pdf Md. Farhad Hossain, Abbas Jamalipour, &

Munasinghe, K. S. (2023). A Survey on Virtual Reality over Wireless Networks: Fundamentals, QoE, Enabling Technologies, Research Trends and Open Issues. https://doi.org/10.36227/techrxiv.24585387.v1

Mohammad Al Khaldy, Abdelraouf Ishtaiwi, al-Qerem, A., & Arya, V. (2023). Redefining E-Commerce Experience: An Exploration of Augmented and Virtual Reality Technologies. ResearchGate; IGI Global. https://www.researchgate.net/publication/376005163_Redefining_E-Commerce_Experience_An_Exploration_of_Augmented_and_Virtual_Reality_Technologies

Mohammadsadeq Herabad, Taheri, J., Ahmed, B., & Calin Curescu. (2024). Optimizing Service Placement in Edge-to-Cloud AR/VR Systems Using a Multi-Objective Genetic Algorithm. Digitala Vetenskapliga Arkivet (Diva) (Karlstad University), 77–91. https://doi.org/10.5220/0012715200003711 Pérez-Muñoz, S., Castaño Calle, R., Morales Campo, P. T., & Rodríguez-Cayetano, A. (2024). A Systematic Review of the Use and Effect of Virtual Reality, Augmented Reality and Mixed Reality in Physical Education. Information, 15(9), 582. https://doi.org/10.3390/info15090582 Rahman,

M. M., Khatun, F., Sami, S. I., & Uzzaman, A. (2022). The evolving roles and impacts of 5G enabled technologies in healthcare: The world epidemic COVID-19 issues. Array, 14, 100178. https://doi.org/10.1016/j.array.2022.100178

Richlan, F., Weiß, M., Kastner, P., & Braid, J. (2023). Virtual training, real effects: a narrative review on sports performance enhancement through interventions in virtual reality. Frontiers in Psychology, 14. https://doi.org/10.3389/fpsyg.2023.1240790

Romagnoli, L., Mattia, G. P., & Beraldi, R. (2023). A Study on Energy Efficiency in Edge-assisted VR Applications with Meta Quest 2 for Disaster Management. IRIS Research Product Catalog (Sapienza University of Rome), 52, 1–7. https://doi.org/10.1109/ictdm58371.2023.10286920 R. Pushpakumar,

Karun Sanjaya, S. Rathika, & B. Rajalakshmi. (2023, July 12). Human-Computer Interaction: Enhancing User Experience in Interactive Systems. ResearchGate; EDP Sciences. https://www.researchgate.net/publication/372338908_Human-Computer_Interaction_Enhancing_User_Experien ce_in_Interactive_Systems

Sharma, M., Tomar, A., & Abhishek Hazra. (2024). Edge Computing for Industry 5.0: Fundamental, Applications and Research Challenges. IEEE Internet of Things Journal, 1–1. https://doi.org/10.1109/jiot.2024.3359297

Sim, D., Baek, Y., Cho, M., Park, S., Sagar, A. S. M. S., & Kim, H. S. (2021). Low-Latency haptic open glove for immersive virtual reality interaction. Sensors, 21(11), 3682. https://doi.org/10.3390/s21113682

Siriwardhana, Y., Porambage, P., Liyanage, M., & Ylianttila, M. (2021). A survey on mobile augmented reality with 5G Mobile edge computing: architecture, applications, and technical aspects. IEEE Communications

Surveys & Tutorials, 23(2), 1160–1192. https://doi.org/10.1109/comst.2021.3061981

Sukhmani, S., Sadeghi, M., Erol-Kantarci, M., & Saddik, A. E. (2018). Edge caching and computing in 5G for mobile AR/VR and tactile internet. IEEE Multimedia, 26(1), 21–30. https://doi.org/10.1109/mmul.2018.2879591

Taleb, T., Nadir, Z., Flinck, H., & Song, J. (2021). Extremely Interactive and Low-Latency Services in 5G and Beyond Mobile Systems. IEEE Communications Standards Magazine, 5(2), 114– 119. https://doi.org/10.1109/mcomstd.001.2000053

Van Damme, S., Sameri, J., Schwarzmann, S., Wei, Q., Trivisonno, R., De Turck, F., & Vega, M. T. (2024). Impact of latency on QOE, performance, and Collaboration in Interactive Multi-User Virtual Reality. Applied Sciences, 14(6), 2290. https://doi.org/10.3390/app14062290

Volk, M., & Sterle, J. (2021). 5G Experimentation for Public Safety: Technologies, Facilities and Use Cases. IEEE Access, 9, 41184–41217. https://doi.org/10.1109/access.2021.3064405

Wang, J., Shi, R., Zheng, W., Xie, W., Kao, D., & Liang, H. (2023). Effect of frame rate on user experience, performance, and simulator sickness in virtual reality. IEEE Transactions on Visualization and Computer Graphics, 29(5), 2478–2488. https://doi.org/10.1109/tvcg.2023.3247057

Witte, K., Bürger, D., & Pastel, S. (2025). Sports training in virtual reality with a focus on visual perception: a systematic review. Frontiers in Sports and Active Living, 7. https://doi.org/10.3389/fspor.2025.1530948

Wong, E. S., Wahab, N. H. A., Saeed, F., & Alharbi, N. (2022). 360-Degree Video Bandwidth Reduction: Technique and Approaches Comprehensive review. Applied Sciences, 12(15), 7581. https://doi.org/10.3390/app12157581

Qian, J., McDonough, D. J., & Gao, Z. (2020). The Effectiveness of virtual reality exercise on individual's physiological, psychological and rehabilitative Outcomes: a systematic review. International Journal of Environmental Research and Public Health, 17(11), 4133. https://doi.org/10.3390/ijerph1711413

Yaqoob, A., Bi, T., & Muntean, G.-M. (2020). A Survey on Adaptive 360° Video Streaming: Solutions, Challenges and Opportunities. IEEE Communications Surveys Tutorials, 22(4), 2801– 2838. https://doi.org/10.1109/COMST.2020.3006999

Zhang, X., pu, zaiyi, & Jiang, X. (2021). Digital Media Technology Application Research Based on 5g Internet of Things Virtual Reality Technology as the Carrier. Research Square (Research Square). https://doi.org/10.21203/rs.3.rs-298090/v1

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