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ENHANCING RESPIRATORY FUNCTION WITH VIRTUAL REALITY: A SCOPING REVIEW

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Abstract Virtual reality (VR) is a promising tool for respiratory rehabilitation (RR), offering immersive environments and biofeedback mechanisms to enhance therapeutic outcomes. This scoping review, following the Arksey and O'Malley framework, evaluated VR systems' effectiveness, design, and implementation for RR. A search of major databases identified 15 studies (2019-2024), including controlled trials (8), design and development studies (2), and various intervention studies. Sample sizes ranged from 2 to 106, totaling 547 participants. Most studies (14/15) reported positive outcomes, such as improved lung function, cognitive function, and quality of life. Common challenges included small sample sizes, homogenous groups, short-term assessments, and technological issues like equipment cost and user interface complexity. Despite these limitations, VR systems show significant promise in enhancing respiratory function and overall health outcomes. Future research should focus on larger, diverse groups, long-term efficacy, and addressing technical challenges to optimize VR-based RR interventions.

Key words: virtual reality, respiratory rehabilitation, biofeedback, immersive environments.

AMS Mathematics Subject Classification: 68-02, 68-04, 68U05

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1 Introduction

Pulmonary rehabilitation (PR) is a "comprehensive intervention based on a thorough patient assessment followed by patient-tailored therapies, which include, but are not limited to, exercise training, education, and behavior change, designed to improve the physical and psychological condition of people with chronic respiratory disease and to promote the long-term adherence of health-enhancing behaviors" [1].

There is a growing evidence-based and real-world experience of delivering PR to people with chronic respiratory disease including chronic obstructive pulmonary disease (COPD), asthma, cystic fibrosis, post-COVID-19, and other respiratory illnesses [2,3]. This growth underscores the necessity of PR in managing chronic respiratory conditions and enhancing patients' quality of life. The British Thoracic Society recently highlighted the increasing interest in alternative models of delivering PR, such as home-based programs, remote supervision, and the use of technology. This interest has been further accelerated by the restrictions placed on face-to-face PR delivery during the global COVID-19 pandemic [4].

VR is an emerging technology that offers a fully immersive and interactive experience, thereby increasing patient engagement and motivation. The immersive nature of VR allows users to fee "present" in a virtual environment, making exercise more engaging and stimulating. By offering a visually rich, dynamic, and customizable environment, VR can significantly increase patient adherence to rehabilitation programs [5, 6]. This immersive approach has been shown to improve not only physical activity but also psychological aspects of rehabilitation, such as reduced anxiety and improved mood [7, 8].

Moreover, VR can utilize biofeedback mechanisms that provide real-time physiological data to both the user and the healthcare provider. Biofeedback sensors (such as heart rate monitors, respiratory sensors, and motion trackers) collect data that allow for adjustments to exercises and rehabilitation procedures, ensuring that each activity is tailored to the patient's current condition. This real-time monitoring not only helps to optimize treatment, but also allows patients to see tangible improvements in their performance, further motivating them to continue their rehabilitation program [5, 9–11]. Biofeedback systems improve the interaction between the patient and the virtual environment, providing continuous feedback that supports personalized treatment approaches.

Despite its potential, there are few published data on the use of VR in PR, and most existing studies have limitations in reporting quality. The acceptability of VR-based PR is also unknown in a patient population traditionally exhibiting digital hesitancy. These PR models, typically delivered remotely, might potentially increase the provision of and accessibility to PR. However, research gaps remain, and these models must be optimized and carefully evaluated before widespread adoption. Critical areas needing further exploration include the development of user-friendly interfaces, assessment of long-term efficacy, and ensuring the integration of biofeedback mechanisms for real-time monitoring and adjustment.

This study aims to review and evaluate the current VR systems developed to enhance respiratory function, assess their effectiveness in improving respiratory health outcomes, and identify the methods, algorithms, and biofeedback mechanisms integrated into these systems. Additionally, the study seeks to highlight current research gaps and propose potential future research directions to enhance the effectiveness and usability of VR-based pulmonary rehabilitation.

2 Methods

A review was conducted according to the recommendations on scoping studies by Arskey & O'Malley [12] to guarantee the application of a rigorous protocol.

Stage 1: Identifying the Research Question

Evidence from related empirical and experimental studies that comprised several types of breathing exercises and patterns was systematically reviewed to address the following research questions:

1. What types of VR systems have been developed to enhance human respiratory function?
2. Have these VR systems demonstrated effectiveness in improving respiratory health outcomes?

3. What methods, algorithms, and biofeedback mechanisms (such as sensors) have been integrated into these VR systems?

4. What are the current research gaps in biofeedback VR systems aimed at improving respiratory health, and what potential future research directions could enhance their effectiveness and usability?

Stage 2: Identifying Relevant Studies

The research was conducted with the use of 3 electronic libraries, which cover a balanced choice of multidisciplinary sources. The libraries were as follows: (1) IEEE Xplore (IEEE), (2) PubMed, and (3) ScienceDirect (SD). The search was delimited to a timeframe of 10 years (2014 to 2024). During the search, the following keywords regarding the virtually applied intervention - “Virtual Reality” - in combination with terms related to the respiratory health - “Pulmonary Rehabilitation” OR “Respiratory System” OR “Breathing Exercise” - were used to create the different search strategies.

Stage 3: Study Selection

The criteria for exclusion of studies in this review was as follows: (1) non original papers; (2) dublicate papers; (3) articles unrelated to VR and breathing; (4) not being able to have full article.

First exclusion: The entries were narrowed down to original papers that were written.

Second exclusion: Duplicate papers, either extracted from one or more libraries, which either produced or concluded the same outcome, were removed from this review.

Third exclusion: Athorough review of the titles and abstracts of studies published in the databases used was performed. For those studies that met the criteria according to title and abstract, a full analysis was performed for further content review.

Forth exclusion: We excluded papers that did not have the full text available.

Additionally, the reference lists of pertinent literature were searched for potentially relevant articles. As a result of this search, five additional articles were identified and included in the review. Two of these articles [6, 8], were found in the reference list of [13]. The other three articles, [7, 10, 11], were identified as studies that cited [5].

Stage 4: Charting the Data

A predesigned data extraction form was used to extract the following data from the included articles: author, year of publication, objective, study design, sample, measures, study duration, biofeedback sensors, VR apparatus, virtual environments, findings, limitations, future research, label (we categorized each study based on the results as positive, negative, or neutral).

Stage 5: Summarizing and Reporting the Results

The data set was subject to quantitative descriptive analysis of article characteristics as well as qualitative thematic analysis of the scope of research on using virtual reality to improve respiratory health.

3 Results

We identified 417 records through electronic database research. After excluding non original papers through electronic filters (n = 308), duplicates (n = 4), articles unrelated to VR and breathing (n = 91), not being able to have full article (n = 4).

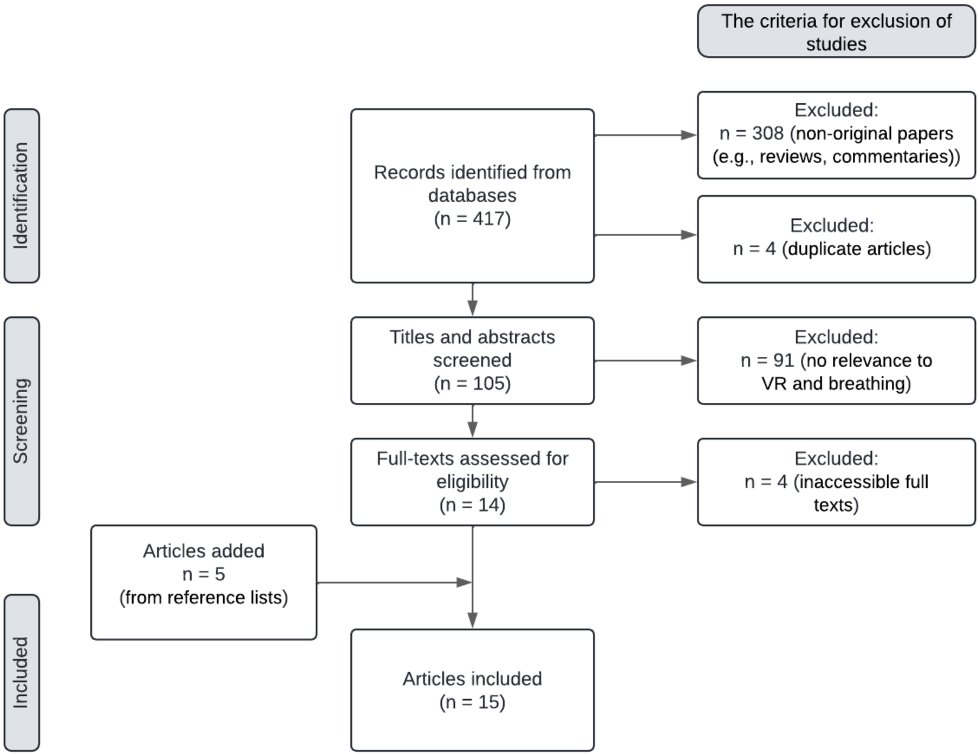

Figure 1: Flow diagram of study selection

Additionally, 5 more relevant articles were identified through the reference lists of pertinent literature. A detailed flowchart is provided in Figure 1. As a result, 15 articles, published between 2019 and 2024, were included in the analysis. As a scoping review, all types of publications have been admitted: 11 journal papers, 4 conference proceedings papers.

The objective and study design of each study are presented in Tab. 1. Most of the reviewed papers were based on controlled studies (8/15). Others included design and development studies (2/15), single-centered, randomized, parallel-group intervention studies (1/15), longitudinal observational studies (1/15), randomized crossover trials (1/15), pre-post intervention studies (1/15), and case studies (1/15).

For instance, Ahmad et al. [14] employed simple randomization using software to generate 1:1 tables and opaque sealed envelopes for the blind allocation of participants. Blum et al. [5] utilized a double-blind personal computer control to enhance the reliability of results. Chittaro et al. [9] divided participants into two groups: real biofeedback (BIO) and placebo biofeedback, i.e. changes in the virtual environment (VE) were controlled by physiological data recordings from the session of another user, randomly selected from the BIO group. In Shi et al. [10], participants were divided into a control group receiving traditional breathing training and an experimental group performing breathing exercises in a virtual environment.

Kang et al. [15] implemented a randomized crossover design where participants experienced both virtual reality for breathing exercises (VR-BRES) and contact breathing exercises (CDB), with the order of interventions varying per participant. Liu et al [16] conducted a randomized controlled trial in which 60 patients were randomly assigned to control and study groups, with 50 participants in each. Before starting the study, it was confirmed that there were no statistically significant differences between the groups, indicating that the groups were comparable.

Table 1: Summary of study objectives and designs

Author	**Objective**	**Study design**	**Sample size per group**
Ahmad et al. (2024) [14]	Assess the effects of VR-simulated treadmill exercise on fatigue, cognitive function, sleep quality, and participant satisfaction in post-COVID-19 subjects	Single-centered, randomized, parallel-group intervention study	n1=8, n2=8
Blum et al. (2020) [5]	Propose and evaluate a novel VR-based approach to respiratory biofeedback using tracked hand controllers to capture and provide feedback on respiration-induced abdominal movements	Randomized controlled laboratory study	n1=36, n2=36
Chittaro et al. (2024) [9]	Propose and evaluate a VR-based biofeedback system designed to teach slow and deep diaphragmatic breathing, investigating its relaxation effects	Controlled trial	n1=18, n2=17
Høeg et al. (2021) [19]	Investigate the feasibility, acceptability, and safety of using VR headsets in a high-intensity interval training (HIIT) exercise program	Longitudinal observational study	n1=3
Kang et al. (2021) [15]	Develop and evaluate the feasibility of a mouth contactless breathing exercise solution using VR for respiratory training	Randomized crossover trial	n1=25, n2=25
Liu et al. (2021) [16]	Analyze the effectiveness of VR technology in lung rehabilitation training for elderly COPD patients with mild cognitive impairment (MCI)	Controlled trial	n1=50, n2=50
Mondellini et al. (2023) [6]	Evaluate the impact of immersive VR on motivation, emotions, and flow state in post-COVID individuals participating in endurance training program	Pre-post intervention study	n1=22
Rockstroh et al. (2020) [7]	Develop and evaluate a VR-based respiratory biofeedback game to promote diaphragmatic breathing	Design and development study	n1=45
Rutkowski et al. (2020) [17]	Compare the benefits of VR training combined with traditional exercise versus exercise alone on physical fitness outcomes	Randomized controlled trial	n1=34, n2=38, n3=38
Rutkowski et al. (2021) [8]	Examine the effectiveness of VR for depression and anxiety in participants with COPD	Randomized control trial	n1=21, n2=20
Rutkowski et al. (2022) [18]	Investigate and compare an innovative in-hospital pulmonary rehabilitation programs augmented with training elements performed in VR	Randomized control trial	n1=16, n2=16
Rutkowski et al. (2023) [13]	Assess the application of VR in pulmonary rehabilitation for patients recovering from post-acute COVID-19	Randomized control trial	n1=18, n2=14
Shi et al. (2023) [10]	Design a biofeedback respiratory rehabilitation training system based on VR technology	Controlled trial	n1=5, n2=5
Tatzgern et al. (2022) [11]	Develop and evaluate the AirRes mask, a VR system for resistance breathing training	Design and development study	n1=12
Wetzel et al. (2019) [20]	Develop and evaluate a VR diving game that incorporates breathing exercises into gameplay	Case study	n1=2

Rutkowski et al. [17] applied a 1:1:1 randomization using Research Randomizer, allocating participants into three groups. Patients in the exercise training (ET) group received a traditional physical rehabilitation (TPR) and strength training program. Participants in the ET + VR group participated in both TPR, strength training, and VR sessions. In the VR group, patients participated in TPR and VR sessions without strength training. The studies by Rutkowski et al. [8,13,18] used 1:1 randomization to assign participants to VR and control groups also using Research Randomizer.

Some studies in our review did not utilize group division, focusing instead on the development and evaluation of VR technologies without comparison to control groups. These studies, such as [6,7,11,19,20], provide important insights into the functionality and potential of VR, despite the absence of control conditions.

The sample characteristics, measures, and study duration of each study are presented in Tab. 2. The total number of participants in this review was 547 (137 males, 225 females, 185 participants for whom gender information was unreported). The age of participants ranged from 19 to 77 years, with a mean age reported in some studies. Of the 15 studies, 3 involved healthy individuals [7,11,15], 4 involved patients with COPD [8,16,17,19], 4 involved post-COVID-19 patients [6,13,14,18], and 1 involved patients with cystic fibrosis [20]. The breathing exercises were mostly related to breathing therapy (13/15) [5–7,9–11,13–17,19,20] and anxiety management (2/15) [8,18].

Several studies [8,10,13,15–18] focused on lung function, using measures such as forced expiratory volume (FEV1, FEV2, FEV3), forced vital capacity (FVC), total lung capacity (TLC), and peak expiratory flow (PEF). FEV1 measures the volume of air (in liters) exhaled during the first second of maximal respiration, with FEV2 and FEV3 extending this measurement to two and three seconds, respectively. FVC represents the total amount of air (in liters) exhaled with maximum force during breathing. TLC represents the maximum volume of air that the lungs can hold. PEF indicates the peak flow rate (in liters per second) achieved during exhalation. FVC and FEV1 are standard parameters of respiration, and PEF is used as a highly reliable indicator for the evaluation of COPD [21].

To assess psychological and cognitive outcomes, studies [7,8,13,14,16,18] used tools such as the Montreal Cognitive Assessment (MoCA), Hospital Anxiety and Depression Scale (HADS), Pittsburgh Sleep Quality Index (PSQI), and Perceived Stress Scale (PSS-10). The MoCA is a cognitive screening test for evaluating cognitive function. The HADS is a 14-item scale that scores 0 to 3 for each item. The first 7 items relate to anxiety, and the remaining 7 relate to depression. A higher score is associated with greater anxiety and symptoms of depression [8]. The PSQI was used to assess sleep quality at baseline and after four weeks through face-to-face interviews with participants [14]. The 10-item Perceived Stress Scale asks participants to rate the frequency of stress appraisals defined by unpredictability, uncontrollability, and overload in a certain period on a scale ranging from 0 = never to 4 = very often [7].

Additionally, several studies [5,6,9,11,19,20] focused on user experience and motivation, using the User Experience Questionnaire (UEQ), Situational Motivation Scale (SIMS), and Intrinsic Motivation Inventory (IMI), the Igroup Presence Questionnaire (IPQ). UEQ measures user experience of interactive products across dimensions such as motivation, emotions, flow, convenience, efficiency, entertainingness, and intention. Participant satisfaction with the exercise program was assessed at the end of the interventions using a 5-point Likert scale, where responses ranged from not at all satisfied to extremely satisfied [14]. User experience was evaluated through four subscales of the UEQ: attractiveness (6 items), perspicuity (4 items), novelty (4 items), and stimulation (4 items) on 7-point semantic differentials [5]. SIMS assesses the type of motivation a person feels in a specific situation. The scale consists of 16 items in total (4 per subscale); the subject expresses the degree of agreement for each sentence on a scale from 1 to 7 [6]. IMI contains 18 items within the subscales of interest/enjoyment, perceived competence, pressure/tension, effort/importance, and value/usefulness [22]. IPQ evaluates the sensation of being present in various virtual environments [11].

Finally, the World Health Organization Quality of Life Scale (WHOQOL-BREF) assesses individuals' perceptions of their position in life [18]. The questionnaire evaluates the quality of life in four categories: physical health, psychological health, social relationships, and environment. It consists of 26 questions with answers organized on a five-point Likert scale [23].

It is important to note that for certain studies, details regarding the duration of virtual reality exposure (VRE) [10,11,13,15,18] and the full experimental session (FES) [9, 10, 15, 20] were reported as "not reported" in Tab. 2. The lack of this information may limit the assessment of the intensity and temporal demands of the interventions.

Table 2: Study samples, measures, and duration

Author	**Sample**	**Measures**	**Study duration**
Ahmad et al. (2024) [14]	16 participants; 30-60 years; post-COVID-19	Chalder Fatigue Scale, MoCA, PSQI, participant satisfaction	VRE: 30-45 min; FES: 4 weeks, 3 days per week
Blum et al. (2020) [5]	72 participants; 16 males, 56 females; 18-49 years; healthy	User Experience Questionnaire, heart rate, respiratory sinus arrhythmia	VRE: 7 min; FES: not reported
Chittaro et al. (2024) [9]	35 participants; 26 males, 9 females; 19-48 years	Biofeedback questionnaire (STAI-S, IPQ, biofeedback, PANAS questionnaires), real-time measurements of userвЂ™s breathing, skin conductance, heart rate	VRE: 50 min; FES: not reported
Høeg et al. (2021) [19]	3 participants; 68-86 years; 2 with COPD, 1 with high risk of cardiovascular disease (CVD)	Heart rate, cadence, perceived exertion (RPE)/ Borg scale, nausea and motivation (IMI)	VRE: 14.5 min; FES: 8 weeks
Kang et al. (2021) [15]	50 participants; 23 males, 27 females; 42.52 (15.76) years; healthy adults	FVC, FEV1, PEF of 1st, 5th, 10th breath, questionnaire (convenience, efficiency, entertainingness, and intention)	VRE: not reported; FES: not reported
Liu et al. (2021) [16]	60 patients; average age: 73.6 years for males, 76.3 years for females; with COPD and MCI	Lung function: lung function meter, FEV1/FVC, COPD assessment test (CAT), MoCA	VRE: 5-15 min; FES: 12 weeks
Mondellini et al. (2023) [6]	22 participants; 6 males, 16 females; 41-69 years; post-COVID	Questionnaires (motivation, emotions, flow), SIMS, heart rate	VRE: 24 min; FES: 3 weeks
Rockstroh et al. (2020) [7]	45 participants; 16 males, 29 females; 19-52 years; healthy	Breath awareness scale, PSS-10, Copenhagen Burnout Inventory, RR, inhalation duration, exhalation duration	VRE: 8 min; FES: 46 min
Rutkowski et al. (2020) [17]	106 patients; 50-70 years; with COPD	Lung function, expiratory volume	VRE: 20 min; FES: 2 weeks, 5 times a week
Rutkowski et al. (2021) [8]	50 participants; 9 males, 41 females; 45-85 years; COPD patients with symptoms of stress, depression, and anxiety	Perception of Stress Questionnaire (PSQ), HADS, lung function, expiratory volume	VRE: 15-30 min (depending on the task); FES: 5 times a week for 2 weeks
Rutkowski et al. (2022) [18]	32 participants; 12 males, 20 females; 40-80 years; post-COVID-19	Lung function, expiratory volume, HADS, WHOQOL-BRIEF	VRE: not reported; FES: 3 weeks, 5 times a week

Author	**Sample**	**Measures**	**Study duration**
Rutkowski et al. (2023) [13]	32 participants; 12 males, 20 females; 41-67 years; post-COVID-19	FEV1, FVC, FEV1/VC, TLC, PSS-10	VRE: not reported; FES: 3 weeks, 5 times per week
Shi et al. (2023) [10]	10 participants; 6 males, 4 females; 56-65 years	FVC, peak flow rate (FEF), flow rate at 25%, 50%, 75% vital capacity (MEF25, MEF50, MEF75), flow velocity difference (FEF), PEF, FEV1, FEV2, FEV3, vital capacity ratio in 1, 2, 3 seconds (V1F, V2F, V3F)	VRE: not reported; FES: not reported
Tatzgern et al. (2022) [11]	12 participants; 10 males, 2 females; age=29 (5.5); excluded with a history of respiratory diseases or issues	IPQ, Borg CR10 scale, Paas rating scale, Single Ease Question (SEQ), VR questionnaire, inhalation and exhalation	VRE: not reported; FES: 75 min
Wetzel et al. (2019) [20]	2 participants; 1 male (18 years), 1 female (20 years), with cystic fibrosis	User Experience Questionnaire, inhalation and exhalation	VRE: 15 - 20 min; FES: not reported

The biofeedback sensors, VR apparatus, and virtual environment of each study are presented in Tab. 3. Our review found that 12 of the 15 evaluated studies [5–11, 13, 15, 18–20] used fully immersive equipment, where the participant's vision is fully enveloped with a head-mounted display (HMD) system. However, 2 of the 15 studies used non-immersive VR equipment, such as a screen connected to a Nintendo Wii Fit Plus game console [14], and an Xbox 360® console with a Kinect® motion sensor, projector, and speakers [17]. Lastly, 1 of the 15 studies did not report the type of VR equipment used [16]. The lack of detailed information about the VR apparatus and biofeedback sensors [8, 16] may hinder comparative analysis and the interpretation of the results.

Various biofeedback sensors are employed across studies, ranging from soft stretch sensors and heart rate bands to advanced motion sensors and custom-built trackers. Remarkably, only 4 of the 15 studies developed their own systems [11,15,19,20]. For instance, Hoeng et al. [19] designed a custom-built wireless tracker attached to the pedal arm. This sensor, connected to a computer via WiFi, featured an Adafruit Feather HUZZAH microcontroller with an ESP8266 WiFi chip and an ITG-3200 gyroscope, powered by a 3.7V, 1200mA LiPo battery. Participants generated forward momentum through virtual environments (VEs), following the road's curves. Kang et al. [15] implemented a mouth contactless respiration measurement using a soft stretch sensor based on liquid metal printing. The VR device and sensor were wired, with content uploaded to a designated server accessed online. Tatzgern et al. [11] developed the AirRes mask utilizing the Sensirion SFM3300 mass flow sensor. Their design included a breathing engine translating sensor measurement into forces, allowing users to manipulate virtual scenes by breathing. The sensor measured airflow bidirectionally for inhalation and exhalation. Wetzel et al. [20] attached an AMS 5812-0600 D differential pressure sensor to a PEP device, accommodating dry and wet gas up to 4137mbar. Connected via I2C to a Pretzel Board (Arduino Nano + Wi-Fi module), it acted as an access point creating a private Wi-Fi network. Clients accessed pressure values through a REST interface during exhalation only. Additionally, Blum et al. [5] developed a custom algorithm using a VR headset's hand controller to capture respiration-induced abdominal movements. This algorithm was also employed in a study by Rockstroh et al. [7], demonstrating its application across different VR scenarios.

The description of VEs ranges from brief to more comprehensive accounts. For instance, studies such as Ahmad et al. [14] and Liu et al. [16] offer succinct descriptions. In contrast, other studies, such as Chittaro et al. [9], provide more detailed descriptions, highlighting elements of interactivity and user action sequences. This variability in the level of detail can complicate the comparison and understanding of the therapeutic potential of different virtual environments.

Many studies [5–10,13,14,18,19] create virtual environments that simulate natural landscapes, such as gardens, parks, and coastal areas, to promote relaxation and enhance the therapeutic experience. Several environments [10,11,15,17,20] incorporate interactive elements and gamified scenarios (e.g., guiding an avatar, collecting rewards, navigating obstacle courses) to increase user engagement and motivation. Below, we present two of the most impressive virtual environments. The first environment was developed by Kang et al. [15], where users engage in a unique training mode featuring an avatar rabbit. During the exercise, users perform deep breaths monitored by a soft stretch sensor, influencing the avatar's ability to navigate obstacles in a VR setting. Successful completion rewards users with virtual carrots, enhancing engagement and motivation. In another innovative study, Tatzgern et al. [11] designed two compelling scenarios using the AirRes mask. The first scenario, an escape room, challenges users to solve tasks using natural breathing interactions, while the second scenario simulates a firefighter obstacle course with environmental challenges like smoke and physical exertion.

Table 3: Biofeedback sensors, VR apparatus, and VE

Author	**Biofeedback sensors**	**VR apparatus**	**Virtual environments**
Ahmad et al. (2024) [14]	Wii remote sensor	Non-immersive setup via Nintendo Wii Fit Plus game console	A jogging track surrounded by trees, providing a naturalistic but non-immersive experience
Blum et al. (2020) [5]	VR controllers, Polar H10 chest strap	Oculus Rift CV1	A natural landscape with elements like hills, rocks, flowers, and swaying trees where elements change color corresponding to the participant's exhalation in the feedback group, and randomly in the control group
Chittaro et al. (2024) [9]	Elastic girth sensor, pair of Ag/AgCI electrodes, photoplethysmograph	Meta Quest 2	A coastal environment with phases: system calibration, fog clearance, interaction with bushes, transitioning to nightfall, and a finale. Voiceover prompts guide user interaction
Høeg et al. (2021) [19]	Custom-build wireless tracker attached to the pedal arm, Polar FT7 sports watches connected to Polar H1 WearLink heart rate sensor	Oculus Rift CV1	A virtual environment featuring expansive natural landscapes with trees, rocks, villages, and a comprehensive road system
Kang et al. (2021) [15]	Soft stretch sensor based on a liquid metal printing technique (FeeltheSame Inc, Korea), portable spirometry Pony FX	Oculus Rift CV1 HMD and controller	Users guide an avatar rabbit through obstacles by performing deep breaths, with the intensity of chest expansion determining the avatar's ability to jump over obstacles and earn rewards

Author	**Biofeedback sensors**	**VR apparatus**	**Virtual environments**
Liu et al. (2021) [16]	Unspecified sensor	Unspecified apparatus	BioMaster scene, a general virtual environment used for respiratory exercises
Mondellini et al. (2023) [6]	Cycle-ergometer with an embedded pulse-oximeter (COSMED ergoline 4), heart rate band (Polar H7)	HTC Vive Pro full kit	The immersive Virtual Park simulates a bicycle ride in a park with naturalistic graphical and audio elements
Rockstroh et al. (2020) [7]	VR controllers	Oculus Quest VR	The game features a stylized, low-polygon 3D environment with natural elements like trees, grass, flowers, and rocks. Inhalation and exhalation trigger temporary changes in the environment, such as color shifts and particle effects
Rutkowski et al. (2020) [17]	Motion sensor (Kinect®)	Xbox 360® console, Kinect® motion sensor, projector with speakers	Patients participated in mini games: 20,000 Leaks, Curvy Creek, Rally Ball, and Reflex Ridge. The games included rafting, cross-country running, hitting a ball in the direction of a player on the screen, and a mountain wagon ride.
Rutkowski et al. (2021) [8]	Unspecified sensor	VR TierOne device	A Virtual Therapeutic Garden inspired by Ericksonian psychotherapy, transforming from dull to vibrant over sessions
Rutkowski et al. (2022) [18]	HR band and pulse oximeter	VR TierOne device	VR relaxation therapy in a virtual garden that transforms from dull to vibrant, symbolizing the patient's progression
Rutkowski et al. (2023) [13]	HR band, pulse oximeter, ergometer (COSMED)	VR TierOne device	Sunny island where the participants conducted a bicycle ride enriched with realistic elements and sound effects to simulate real-life situations
Shi et al. (2023) [10]	HKF-20C vital capacity sensor	HTC Vive Pro 2	Two scenes: "Blowing out candles" in an indoor environment and "Dandelion Blowing" in a park setting. Users achieve respiratory training goals by blowing on objects, supported by voice prompts for enhanced engagement
Tatzgern et al. (2022) [11]	Sensirion SFM3300 mass flow sensor, 3M 6000 series respirator mask, Motor SG-90 servomotor	Oculus Quest 2 HMD	Two scenarios: an escape room with tasks involving natural breathing interactions and a firefighter obstacle course simulating breathing resistance and environmental conditions like smoke
Wetzel et al. (2019) [20]	AMS 5812-0600 D differential pressure sensor, PEP device	Lenovo Mirage headset, Samsung Galaxy 8 smartphone with Google Daydream View, 3DoF controller	Underwater path with marine life and shipwrecks, where users navigate by exhaling, with visual cues like a pressure gauge and rewards to enhance engagement

The findings, limitations, and future study directions of each study are presented in Tab. 4. Based on the review of VR studies, the findings underscore VR as a promising and effective approach for enhancing various health outcomes. Among the 15 studies reviewed, 14 reported positive outcomes, with only one study showing neutral results. Several studies showcased significant improvements in physical fitness and exercise tolerance among participants. For example, Rutkowski et al. [17] noted positive effects on physical fitness in COPD patients through VR training. Shi et al. [10] emphasized enhanced lung function achieved via visualized respiratory data in VR rehabilitation programs. VR interventions [7, 8, 14, 16] were also identified for their positive impact on cognitive function and mental health. Studies [13, 14] consistently demonstrated improvements in overall quality of life and patient satisfaction with VR-based interventions. Moreover, the research highlighted the effectiveness of integrating biofeedback systems with VR to enhance breath awareness and overall therapeutic experience.

Despite the promising outcomes observed in VR-based respiratory rehabilitation, several limitations were noted across the reviewed studies. 5 of the 15 studies [6, 9, 10, 14, 19] had small participant numbers, potentially limiting the generalizability of their findings. Moreover, some studies [7, 9] had homogenous participant groups, often with similar demographic profiles or clinical conditions, which restricts the applicability of results to diverse populations. Some studies [7, 9, 10, 17, 18] primarily focused on short-term outcomes, lacking sufficient longitudinal assessments to evaluate the sustainability of benefits over time. Additionally, several studies [5, 7] lacked control groups, posing challenges in establishing causal relationships between VR interventions and observed improvements. Technical issues related to VR equipment, such as the bulkiness of head-mounted displays and limitations in data transmission accuracy, were reported in multiple studies [10, 15]. Specific studies [5, 20] cited limitations in measurement tools and methodologies, potentially impacting the reliability and accuracy of reported outcomes.

Future research in VR-based respiratory rehabilitation should address several key areas highlighted by the reviewed studies. Firstly, conducting randomized controlled trials with larger and more diverse participant groups will enhance the generalizability of findings [14, 16]. Longitudinal studies are essential to assess the sustained efficacy of VR interventions over extended periods [5–9, 17, 20]. Addressing technical challenges, including improving the design and usability of VR equipment is crucial for optimizing user experience and data accuracy [10, 11, 15]. Furthermore, future studies [6–9, 11, 13, 15–20] should explore innovative methodologies and measurement tools to enhance the reliability and precision of outcome assessments in VR-based respiratory rehabilitation.

Table 4: Study findings, limitations, and future research

Author	**Findings**	**Limitations**	**Future research**	**Label**
Ahmad et al. (2024) [14]	Significant improvements in fatigue, cognitive function, and sleep quality were observed in both groups ($p < 0.05$), with the VR group reporting higher satisfaction with the exercise program ($p = 0.037$)	Small sample size, no non-exercising control group, unblinded interventions	Conduct larger randomized controlled trials to assess long-term effects of VR on fatigue, cognitive function, and sleep quality in post-COVID-19 patients	Positive
Blum et al. (2020) [5]	Improved user experience, breath awareness, slow diaphragmatic breathing, and increased respiratory sinus arrhythmia	Controlled environment, subjective breath awareness, unvalidated respiratory measurements, and approximations of respiratory rate	Investigate broader applicability and long-term effects of biofeedback in VR on respiratory function	Positive
Chittaro et al. (2024) [9]	Biofeedback in VR induced relaxation, enhanced presence, emphasizing biofeedback's importance in VR	Small, predominantly male sample, no long-term effect assessment	Explore impacts of visual/auditory elements, conduct longitudinal studies on relaxation effects	Positive

Author	**Findings**	**Limitations**	**Future research**	**Label**
Høeg et al. (2021) [19]	VR maintained motivation without increasing dyspnea or cardiovascular demands	Small sample size limits external validity	Explore ways to enhance motivation in VR-based HIIT programs, emphasize interactive features	Positive
Kang et al. (2021) [15]	Higher mean scores for respiratory parameters in VR-BRES vs. CDB: FVC (Z = 4.82, 4.95, $p < .001$), FEV1 (t = 6.02, 6.26, $p < .001$), PEF (t = 5.35, 5.68, $p < .001$). Higher user evaluation for efficiency (Z = 3.86, $p < .001$), entertainingness (Z = 5.00, $p < .001$), and intention to use (Z = 3.22, p = .001), with no difference in convenience (Z = -0.90, p = .369)	Prototype VR-BRES, bulky HMD, no double-blind procedures, focus on training parameters only	Add wireless Bluetooth sensors, 2D training content, and conduct clinical studies on health outcomes	Positive
Liu et al. (2021) [16]	Higher FEV1 and FEV1/FVC in the study group vs. control ($P < 0.05$). The study group showed a longer 6-minute walking distance, lower CAT score, and higher MoCA score than those in the control group ($P < 0.05$)	Lacked objective quantitative indicators	Expand sample sizes, employ rigorous study designs, integrate VR with traditional Chinese medicine	Positive
Mondellini et al. (2023) [6]	High motivation scores (Intrinsic: p = 0.003, Identified Regulation: p = 0.006, External Regulation: p = 0.015), increased flow (p = 0.024), and decreased amotivation ($p < 0.001$), indicating potential for sustained exercise	Validate with larger sample size, explore variables like competence and attitudes	Extend to other contexts, implement pulmonary rehab programs for long-term motivation	Positive
Rockstroh et al. (2020) [7]	Increased breath awareness, improved diaphragmatic breathing, increased relaxation, reduced stress and burnout	Lack of control group, no long-term assessment, homogenous sample	Address generalizability, long-term stability, compare with existing treatments, fine-tune training	Positive
Rutkowski et al. (2020) [17]	The ET+VR group outperformed the ET group in the Arm Curl ($p < 0.003$), Chair Stand ($p < 0.008$), Back Scratch ($p < 0.002$), Chair Sit and Reach ($p < 0.001$), Up and Go ($p < 0.000$), and 6-Minute Walk Test ($p < 0.011$). The VR group also surpassed the ET group in the Arm Curl ($p < 0.000$), Chair Stand ($p < 0.001$), and 6-Minute Walk Test ($p < 0.031$)	Limited to GOLD 2 and 3 stages, focused on 2-week in-hospital program	Investigate effects in longer-term outpatient settings, assess game-training satisfaction	Positive

Author	**Findings**	**Limitations**	**Future research**	**Label**
Rutkowski et al. (2021) [8]	The VR group showed significant reductions in stress levels ($p < 0.0069$, $d = 0.353$), depression ($p < 0.001$, $d = 0.836$), and anxiety ($p < 0.0009$, $d = 0.631$), with medium to strong effect sizes	Excluded comprehensive spirometry data, follow-up assessments needed	Include objective stress measures, conduct long-term follow-up studies	Positive
Rutkowski et al. (2022) [18]	Both groups showed significant improvements in depression (VR: $p = 0.008$; CG: $p = 0.017$) and anxiety (VR: $p < 0.001$; CG: $p = 0.003$). No significant improvements in quality of life were observed in either group	Preliminary results, need follow-up assessments and long-term quality of life analysis	Include follow-up assessments, extend quality of life analysis	Neutral
Rutkowski et al. (2023) [13]	VR rehabilitation improved exercise performance and reduced dyspnea levels, which can improve patientsвЂ™ quality of life and ability to perform daily activities	Excluded full spirometry data, omitted symptom onset time, preliminary results	Include broader diagnostic tools, conduct follow-up assessments	Positive
Shi et al. (2023) [10]	Enhanced lung function with quantified, visualized respiratory data, improved rehab effectiveness, engaging training	Small sample size, short-term evaluation, accuracy of data transmission	Improve respiratory data collection and transmission accuracy	Positive
Tatzgern et al. (2022) [11]	AirRes mask enhances training, promoting better breathing awareness	Did not address prolonged use or potential discomfort	Refine input channels for improved interaction, apply in therapeutic exergames	Positive
Wetzel et al. (2019) [20]	Initial impressions and user tests have been encouraging. Both the underwater diving experience as well as using a VR headset were positively received	Variations in distraction levels	Incorporate procedural content generation, customize game distractions, conduct long-term user study	Positive

4 Discussion

This review highlights the burgeoning potential of VR systems in enhancing human respiratory function, drawing from a diverse range of study designs and outcomes. The majority of the studies were controlled trials, which provide robust evidence for the effectiveness of VR interventions in respiratory health. Controlled trials offer a high level of evidence due to their ability to reduce bias through randomization and control groups. The various designs used, including randomized crossover trials, longitudinal observational studies, and pre-post intervention studies, underline the adaptability and wide applicability of VR systems across different contexts and populations.

The VR interventions were primarily aimed at improving lung function, cognitive and psychological outcomes, and user experience. A substantial number of studies focused on populations with COPD and post-COVID-19 conditions, highlighting the clinical relevance of VR systems in managing respiratory diseases. The use of diverse measures such as FEV1, FVC, and TLC, alongside cognitive and psychological assessments like the MoCA and HADS, underscores the multifaceted impact of VR interventions on both physical and mental health.

A critical observation from the review is the significant variation in VR equipment and biofeedback sensors used. Fully immersive VR systems, where the participant's vision is entirely enveloped by a head-mounted display, were prevalent in 12 out of 15 studies. This immersive experience is crucial in creating realistic and engaging virtual environments that can enhance therapeutic outcomes. However, the review also highlighted the challenges related to the bulkiness and data transmission accuracy of these devices, which need to be addressed in future research to improve usability and effectiveness.

The integration of biofeedback mechanisms within VR systems is a notable advancement, as it allows real-time monitoring and adjustment of respiratory parameters, thereby enhancing the therapeutic experience. The development of custom-built sensors and interactive virtual environments reflects the innovative approaches being explored to optimize respiratory rehabilitation. For instance, studies utilizing custom sensors for breath monitoring and interactive elements like avatar navigation and gamified scenarios demonstrated higher user engagement and motivation.

Despite the promising findings, the review identified several limitations across the studies. Small sample sizes and homogeneous participant groups limit the generalizability of the results. Additionally, many studies lacked long-term follow-ups, making it challenging to assess the sustained impact of VR interventions. The absence of control groups in some studies also complicates the establishment of causal relationships between the interventions and observed improvements.

5 Conclusion

The reviewed studies collectively suggest that VR systems hold substantial promise in improving respiratory function, cognitive outcomes, and overall user experience. The integration of immersive VR environments and biofeedback mechanisms can significantly enhance the effectiveness of respiratory rehabilitation programs. However, there is a clear need for future research to address the current limitations by conducting larger, more diverse, and longer-term studies. Improving the design and usability of VR equipment and developing more precise measurement tools will be crucial in advancing this field. Overall, VR interventions represent a novel and effective approach to respiratory rehabilitation, with the potential to be integrated into routine clinical practice to benefit a wide range of patient populations.

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