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REVIEW

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Enhancing lower-limb rehabilitation: a scoping review of augmented reality environment

Yuanyuan Liu[1*], Qiong Zhang[1] and Weiyi Li[1]

Abstract

Background Lower-limb rehabilitation is crucial for restoring motor function in individuals with physical impairments; however, traditional rehabilitation approaches often encounter challenges such as limited resources and reduced patient motivation. Augmented reality (AR) offers an innovative approach by enriching rehabilitation with interactive and engaging experiences, thereby enhancing both motivation and treatment outcomes. AR environments enable patients to practice exercises in an immersive setting that emulates real-life scenarios, potentially increasing adherence and improving functional recovery.

Methods This scoping review analyzed 25 peer-reviewed studies on the use of AR within the "Environment" component of the Human–Computer-Environment system for lower-limb rehabilitation. We present a taxonomy of existing AR systems, categorizing them by rehabilitation tasks (content) and interaction modes (form), which identify both physical and virtual elements that contribute to a supportive AR environment.

Discussion The findings suggest that well-designed AR environments offer a flexible and cost-effective approach to various rehabilitation tasks. Customization is essential for addressing specific rehabilitation stages, including muscle strengthening, balance improvement, and gait training. The integration of multisensory feedback, such as visual, auditory, and haptic cues, enhances patient engagement and provides real-time performance monitoring. Effective AR environments must also account for the distinct needs of each limb, particularly for bilateral impairments, and ensure sufficient space for safe movement. By providing an individualized rehabilitation experience, AR environments have the potential to significantly improve patient motivation and outcomes. Future research should explore the integration of AR environments with assistive technologies, such as wearable devices and exoskeletons, to further enhance rehabilitation possibilities.

Keywords Augmented reality, Lower-limb rehabilitation, AR environment design, Multisensory interactions, Motor function recovery

Introduction

With an aging global population and an increasing prevalence of strokes and spinal cord injuries, approximately 2.4 billion people globally live with conditions that could benefit from rehabilitation [1]. Appropriate physical rehabilitation, aimed at restoring or enhancing physical abilities for daily activities such as walking and eating, is essential for recovering lower-limb motor function and improving overall healthcare outcomes [2]. Nonetheless,

*Correspondence:
Yuanyuan Liu
yuanyuanliu@buaa.edu.cn
[1] Department of Industrial Design, School of Mechanical Engineering and Automation, Shahe Campus, Beihang University, No. 9 Nansan Road, Shahe Higher Education ParkChangping District, Beijing 102206, China

traditional therapist-supported rehabilitation is frequently constrained by space, time, and human resources [3]. Additionally, in settings with minimal therapist supervision, patients may engage passively and receive insufficient feedback on their progress [4].

Augmented reality (AR), which overlays digital information onto the user's physical environment in real-time, has progressively enhanced the rehabilitation experience for patients with lower-limb injuries. AR's capability to deliver immersive first-person interactive experiences has demonstrated improvements in learning, behavior, and emotional responses [5]. Moreover, an AR system, comprising AR display devices coupled with various monitoring and feedback technologies, facilitates the development of rich interactive scenarios for rehabilitation training even within limited spaces [6, 7]. Unlike fully immersive virtual reality (VR) environments, AR emphasizes a seamless fusion of real and virtual worlds. Virtual cues are overlaid on the patient's familiar real environment, allowing for naturalistic rehabilitation tasks that minimize the need to "translate" trained behaviors to the real-world context [8], potentially reducing patient anxiety [9].

Despite challenges in implementing AR hardware and software systems, including issues with depth perception, real-time 3D holography, simultaneous localization and mapping (SLAM), and the integration of software development kits (e.g., Unity, Unreal [10–12]), a well-designed AR environment is crucial for ensuring enjoyable rehabilitation tasks and engaging interaction modes [13]. The AR-based lower-limb rehabilitation training system can be viewed as a complex interaction system, where the three components of the Human–Computer-Environment system collectively influence rehabilitation outcomes [14]. The "Human" component encompasses patients with lower-limb injuries, focusing on their perceptions and needs. The "Computer" component comprises AR devices and assistive rehabilitation devices such as robotic exoskeletons and inertial measurement units (IMUs). Although numerous studies have explored human–computer interaction (HCI) and demonstrated its significant impact on patient motivation and engagement [15, 16], existing research emphasizing AR's benefits tends to overlook the "Environment" aspect. This component should encompass both intrinsic features of the physical setting (e.g., lighting, spatial layout, flooring) and the contextual interfaces that connect it to the user and to the AR system. The Rehabilitation 2030 Initiative by the World Health Organization, for instance, highlights environmental interactions as a vital element of the rehabilitation system to enrich patient experience.

Recent studies and reviews have discussed AR-assisted physical rehabilitation from various perspectives: for example, comparing interaction technology versus environmental considerations, AR versus VR/MR/XR technologies, and distinctions between upper and lower limb rehabilitation. Prior reviews have investigated AR technology in physical rehabilitation within the broad field of HCI, including AR hardware systems [17], software systems [18], and their integration with other assistive technologies [19, 20]. Moreover, existing reviews predominantly discuss VR technology or the broader spectrum of mixed realities (AR, VR/MR/XR) in rehabilitation contexts [17, 18, 20–22]. When evaluating VR and AR technologies from an environmental perspective, it is crucial to distinguish AR environments, which synthesize real and virtual environmental elements, from VR's purely virtual environments [23]. Additionally, current research exhibits a significant focus on AR-based systems for upper limb rehabilitation, underscoring an underrepresentation of lower limb applications [17, 18, 24, 25].

This review aims to address this gap by examining the application of AR environments in lower-limb rehabilitation. The primary objective is to map and summarize the available literature on AR environments in lower-limb rehabilitation, consistent with the goals of a scoping review. Unlike systematic reviews that focus on synthesizing evidence to evaluate the effectiveness of interventions, a scoping review allows a broader exploration of diverse AR systems and their environmental components. Specifically, this review provides a new perspective on the environmental role in AR-based lower-limb rehabilitation, differentiates the AR rehabilitation environment from those of VR or XR, and offers insights and guidance for integrating AR into lower-limb rehabilitation. This review is structured by the following research questions.

RQ1: From the perspective of Human–Computer-Environment system, what elements define the AR environment for lower-limb rehabilitation?

RQ2: What are the key factors guiding the design of an AR environment tailored for lower-limb rehabilitation?

RQ2-1: What specific rehabilitation tasks are conducted within AR environments designed for lower-limb rehabilitation?

RQ2-2: What forms of interaction are implemented in AR environments to facilitate the lower-limb rehabilitation process?

RQ3: How can the design of the AR environment be improved to increase engagement in lower-limb rehabilitation training?

Methods

This review investigates the use of AR environments in lower-limb rehabilitation. Our objective is to elucidate the opportunities and challenges presented by AR and to inform the design of effective AR rehabilitation systems. We examined a broad spectrum of AR applications in lower-limb rehabilitation scenarios, considering various interaction modes, environmental elements, and potential integrations with assistive technologies, including robotic exoskeletons. Employing the PICO (Population, Intervention, Comparison, Outcome) approach [26], we selected and analyzed studies involving individuals with lower-limb injuries (Population) assisted by AR technologies (Intervention), compared to traditional therapist-assisted methods (Comparison), with a primary focus on rehabilitation tasks and human–computer interaction (Outcome). This scoping review was conducted in accordance with the adapted PRISMA-ScR guidelines [27] and the methodological framework proposed by Arksey and O'Malley [28]. The full review protocol was completed before screening began and assessed by external experts. It is now publicly available on OSF (https://doi.org/10.17605/OSF.IO/8CR39), demonstrating our commitment to transparency and rigor. The review process is illustrated in Fig. 1.

Identification: Our research questions span multiple disciplines, including HCI, industrial design, medical rehabilitation, and psychology. Given this interdisciplinary scope, we conducted a comprehensive search across multiple databases, including all relevant indices within Web of Science (e.g., MEDLINE, Derwent Innovations Index, KCI-Korean Journal Database), Science Direct, IEEE Xplore, and ACM Digital Library. The search strategy used the following query strings: ("lower-limb" OR walk* OR gait) AND ("rehabilitation" OR "rehabilitation environment") AND ("augmented reality" OR "mixed reality"). Additional filters, such as limiting results to English-language publications, were applied when available. The literature search was performed between 8 October 2023 and 10 January 2024 and our review was limited to publications from 2013 to January 2024. This timeframe was chosen because the commercialization of AR technologies (e.g., the release of Google Glass in 2012), marked a turning point in the development and application of AR in rehabilitation. Consequently, research into AR-based lower-limb rehabilitation gained momentum from 2013 onward, ensuring that our review captures the most relevant and up-to-date insights into the field. A total of 705 records were initially retrieved. After removing duplicates using Zotero (which identified 35 duplicates), 670 unique articles remained for screening.

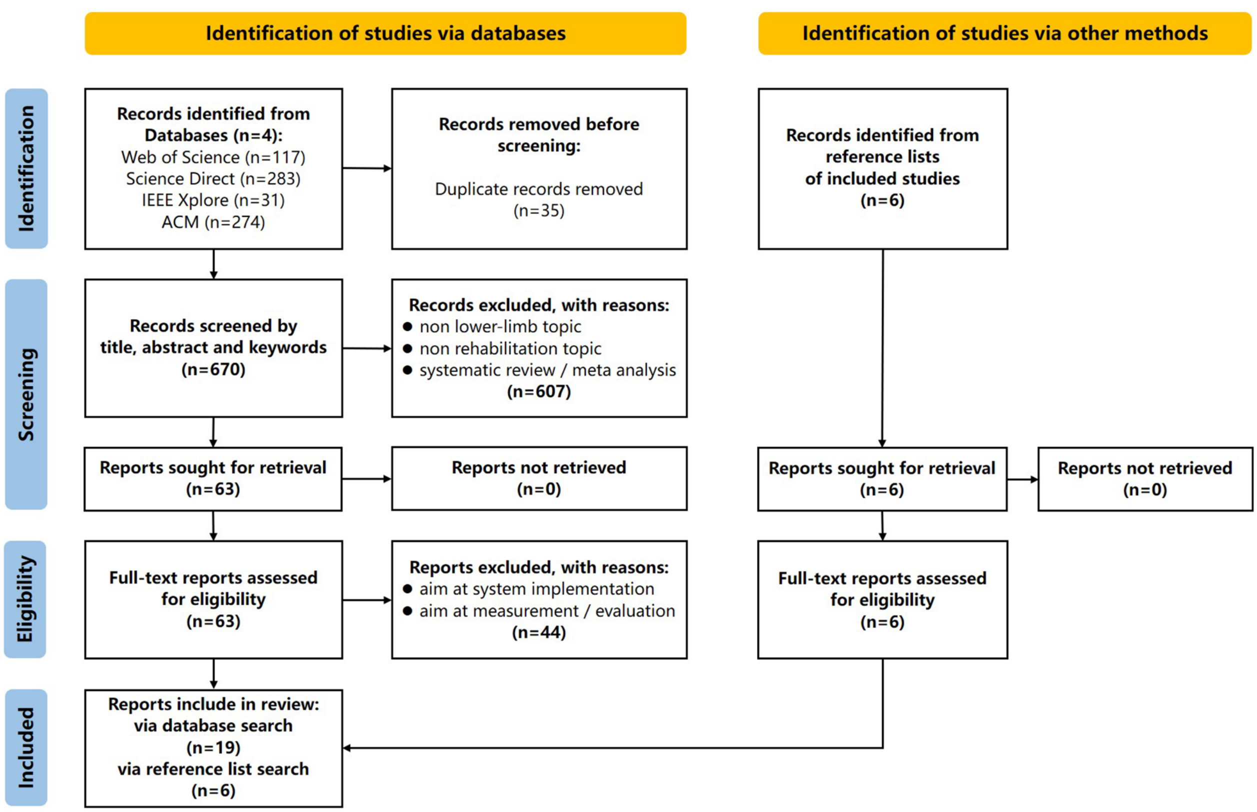

Fig. 1 Review Process

Screening: Two primary researchers independently conducted the initial screening of the 670 papers, reviewing each paper's title, abstract, and keywords to determine its suitability. Each paper was reviewed twice to ensure thoroughness. In cases of disagreement, the paper was marked for discussion with a third expert. Papers were excluded based on the following criteria: i) the primary focus was not lower-limb rehabilitation (e.g., applications in surgery, cognitive rehabilitation, or medical education); ii) the paper was a systematic review or meta-analysis. This screening excluded 607 papers, leaving 63 papers eligible for further assessment.

Eligibility: The remaining 63 papers underwent a full-text review by the two primary researchers, with each paper being independently examined twice. Papers with conflicting inclusion decisions were marked for further review. A third researcher subsequently reviewed all included and flagged papers to mitigate bias. The three researchers then discussed each flagged paper to reach a consensus. Papers were excluded at this stage for the following reasons: i) the paper focused solely technical implementation details of AR systems (with no rehabilitation evaluation); ii) the paper evaluated rehabilitation effectiveness without detailing specific rehabilitation tasks or interaction modes. Applying these exclusion criteria, 44 papers were excluded during the eligibility assessment, leaving 19 papers. Additionally, a snowball search during the full-text review identified 6 more relevant papers. Ultimately, 25 studies met our inclusion criteria and were selected for further analysis.

Analysis and synthesis: The analysis of the 25 studies involved a four-step qualitative coding process: i) *Initial Open Coding*: One researcher openly coded a small sample of four papers to identify sub-dimensions under the two main dimensions of rehabilitation tasks and interaction modes. ii) *Sub-dimension Evaluation*: Both primary researchers then assessed the relevance and completeness of these sub-dimensions for AR environment design. Sub-dimensions were merged, expanded, or removed as necessary to better align with the research objectives. iii) *Systematic Coding*: The two researchers systematically coded all 25 studies to extract data related to the defined sub-dimensions and the environmental elements within the AR systems. Any inconsistencies in coding results were discussed and resolved. iv) *Review and Revision*: Finally, the coding results were reviewed by a third researcher to ensure accuracy and clarity in the definition of sub-dimensions. Terminology was refined to minimize potential misunderstandings.

Results

A primary focus of our analysis was the integration of physical and virtual environmental elements within AR systems for lower-limb rehabilitation training. We proposed a reference framework (Fig. 2) to optimize the coordination of these elements within the AR environment and bolster support for lower-limb rehabilitation (addressing RQ1). We also developed a taxonomy of AR systems tailored to lower-limb rehabilitation (Fig. 3), identifying rehabilitation tasks and interaction modes as the two primary design dimensions guiding the design

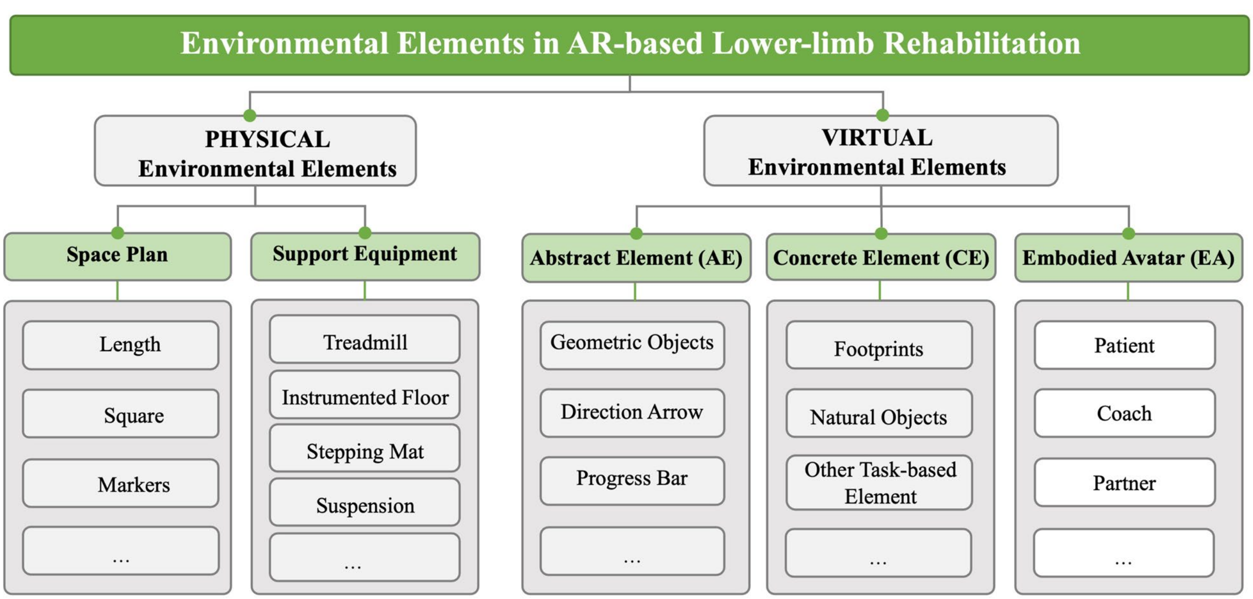

Fig. 2 Environmental Elements in AR-based Lower-limb Rehabilitation

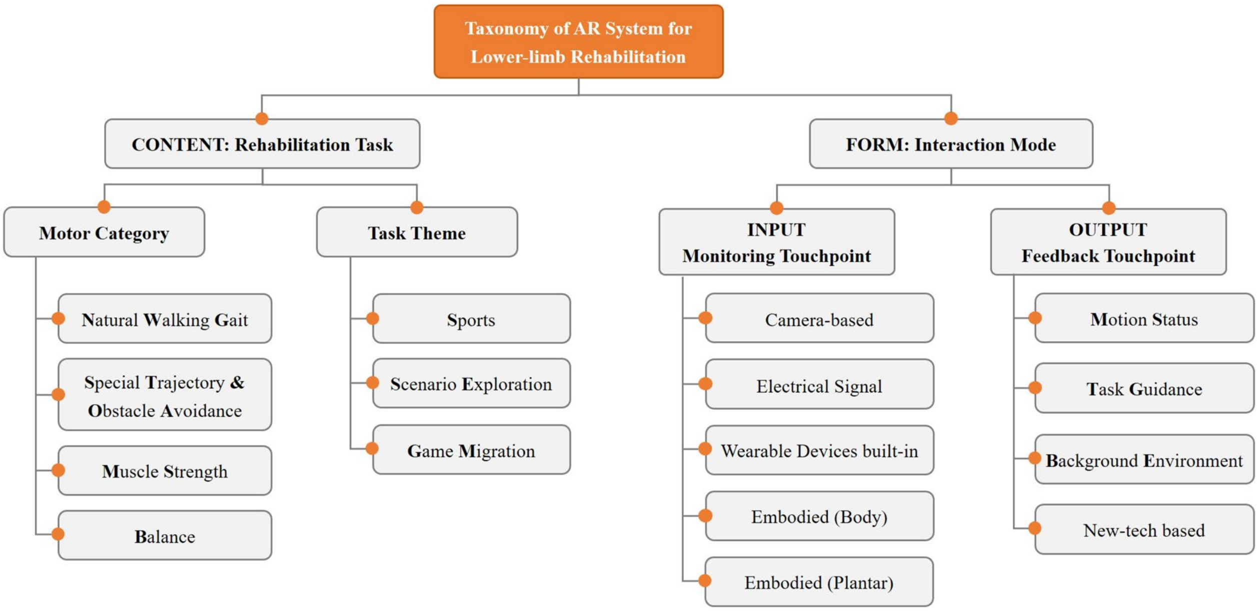

Fig. 3 Overview of the Taxonomy of AR Systems for Lower-limb Rehabilitation

of AR environments (addressing RQ2). The 25 selected studies were structured around the taxonomy's sub-dimensions, focusing on motor categories, task themes, and the detailed content of the rehabilitation tasks, as well as on monitoring and feedback devices, information types, and sensory modalities underpinning interaction modes. Drawing on insights from both the framework and the taxonomy, we explored strategies to utilize these structured elements to improve engagement in lower-limb rehabilitation (addressing RQ3). The results of data extraction from the 25 studies are summarized in Table 1. We examined how various environmental elements contribute to enhancing the rehabilitation training experience, particularly by optimizing rehabilitation tasks and interaction modes.

Across the 25 studies, 452 participants (and 18 to 83 years; both male and female) participated in AR-based rehabilitation settings. Their physical conditions ranged from healthy individuals to patients with stroke, Parkinson's disease, and multiple sclerosis.

Physical and virtual elements for AR environment design in lower-limb rehabilitation (RQ1)

This scoping review further examined the physical and virtual environmental components of AR environments across 25 studies and proposed a structured framework to facilitate task execution and optimize interaction experiences in lower-limb rehabilitation. AR environments are fundamentally divided into physical and virtual segments (Fig. 2). The physical environment refers to the tangible spatial setting in which rehabilitation activities are conducted, encompassing essential physical infrastructures. Various physical environmental elements, including temperature, light, color choices, flooring materials, and artistic landscapes, have been considered to optimize these surroundings [54]. Conversely, the virtual environment encompasses digital overlays provided by AR systems, which enrich the real-world settings with rehabilitation-focused information. The effective design of AR-based rehabilitation scenarios depends on the seamless integration of both physical and virtual components to enhance the overall quality and impact of the rehabilitation process.

Physical environmental elements in AR environments typically comprise two main components: space planning and support equipment. To accommodate diverse movements and rehabilitation-task themes, the design of AR environments must integrate physical features that facilitate training. For straightforward walking tasks, space planning generally required a linear area ranging from 10 to 25 m in length [31, 34, 36, 38]. More complex tasks necessitate dedicated square spaces with dimensions tailored to the scenario. For example, a 3 ×5-m space was used for a "*gold ingot treasure hunt*" [44], while a 14 ×4-m area was required for a slalom course featuring virtual lamps [41]. The strategic arrangement of markers within these spaces is crucial for defining AR environments [45, 46]. Certain rehabilitation exercises also mandate specialized support equipment, ranging from treadmills for gait exercises [37] to instrumented surfaces

Table 1 Data Extraction from the 25 Included Studies

References	Rehabilitation Task		Interaction mode					Environmental elements	
	motor category [a]	Task theme [b]	Content	Input devices	Output devices	Sensory modality	Feedback information [c]	Physical	Virtual
Wang et al. (2023) [29]	NWG	–	Complete joint movements of walking	EEG cap	MR headset (HoloLens)	Visual	MS	–	Abstract Element (Blocks)
Evans et al. (2022) [30]	NWG	–	Change walking speed	Force sensors	MR headset (HoloLens)	Visual	MS, TG	Support Equipment (instrumented floor)	Abstract Element (holographic ball)
Guinet et al. (2022) [31]	NWG	–	Walk at predefined speed	HMD built-in IMU, cameras	MR headset (HoloLens)	Visual Auditory	MS, TG, BE	Space Plan (15 m long)	Abstract Element (Round shape)
Miller et al. (2022) [32]	NWG	–	Walk in a straight line	HMD built-in IMU	MR headset (HoloLens)	Visual Auditory	TG, BE	–	Embodied Avatar (Partner)
Ko et al (2021) [33]	NWG	GM	Make steps forward on corresponding side of the track	HMD built-in IMU, EEG cap (Notch)	MR headset (HoloLens)	Visual Auditory	MS, TG	–	Abstract Element (Blue tracks), Concrete Element (White ball, Rainbow bullets)
Hidayah et al (2019) [34]	NWG	–	Walk 6 laps of 25 m	IMUs placed on the cuffs of exoskeleton	MR headset (HoloLens)	Visual Haptic	MS	Space Plan (25 m long)	Abstract Element (holographic blue spheres with connective white rendered lines)
Hurtado et al (2019) [35]	NWG	–	Walk in a straight line	Camera (Nikon 7100)	PC	Visual	MS, BE	Space Plan (marker*3)	Abstract Element (Lines, Squares)
Bennour et al (2018) [36]	NWG	–	Walk on the instruction footprint	Optoelectronic motion capture device (Vicon)	Video Projector	Visual	MS, TG	Space Plan (10 m long walkway)	Concrete Element (Footprints)
Sekhavat et al (2018) [37]	NWG	–	Perform gait training exercises	Camera (Kinect V1)	Video Projector	Visual	TG, BE	Support Equipment (treadmill)	Abstract Element (Red lines, Cubes), Concrete Element (Footprints)
Ahn et al (2017) [38]	NWG	–	Walk along a straight line	HMD built-in IMU	AR smart glasses (Epson BT-200)	Visual	TG, BE	Space Plan (10 m long)	Abstract Element (Lines)
David et al. (2023) [39]	NWG	–	Walk to reach the correct trunk position	IMU fixed in the chest	MR headset (HoloLens 2)	Visual Auditory	MS, TG	Support Equipment (exoskeleton)	Abstract Element (red dot and yellow dot)
Amiri et al (2022) [40]	ST&OA	SE	Put feet on the determined colored markers	Camera (Kinect V2)	Video Projector	Visual Auditory	TG, BE	Space Plan (1 ×1.2 m), Marker*6 (25 ×40 cm)	Concrete Element (Bricks, Plants)
Held et al (2020) [41]	ST&OA	SE	Overstep virtual obstacles, walk slalom with lamps, and perform dual-task math calculation	IMU*7 (Xsens MVN)	MR headset (HoloLens 2)	Visual Auditory	TG, BE	Space Plan (14 × 4 m)	Abstract Element (Direction arrows, Buttons), Concrete Element (Tree trunks, Stones, River, Ridge-path, Lamps)

Table 1 (continued)

References	Rehabilitation Task		Interaction mode					Environmental elements	
	motor category [a]	Task theme [b]	Content	Input devices	Output devices	Sensory modality	Feedback information [c]	Physical	Virtual
Jassen et al (2020) [42]	ST&OA	GM	Perform 180° turns around their axes	Camera*2 IMU*17 attached to body parts (Xsens MVN)	MR headset (HoloLens)	Visual Auditory	TG	Space Plan (50 × 50 cm)	Abstract Element (Yellow sphere)
Luchetti et al (2020) [43]	ST&OA	–	Step over virtual obstacles while avoiding contact	Camera (Kinect V2)	MR headset (HoloLens)	Visual	TG, BE	–	Embodied Avatar (Patient)
Wang et al (2020) [44]	ST&OA	SE	Walk straight and perform turning maneuvers	HMD built-in camera	VR headset (HTC Vive Pro, with an AR function)	Visual Auditory	TG, BE	Space Plan (3 × 5 m)	Concrete Element (Gold ingots, Caves)
Chessa et al (2017) [45]	ST&OA	GM	Play with a virtual hopscotch, launch a small box on a given number	Camera (Kinect V1)	Smartphone (Samsung S5); VR headset (VIGICA 360)	Visual	TG	Support Equipment (Real hopscotch)	Concrete Element (Hopscotch-virtual lines and numbers)
Zhu et al (2022) [46]	MS	–	Lower extremity therapeutic exercises*10 (front lunge, standing knee bend, seated knee, single leg deadlift, straight leg raise side, terminal knee extension, single leg squat, sit to stand, standing fire hydrant, single leg bridge)	Camera*29 (OptiTrack)	VR headset (HTC Vive Pro2, with an AR function)	Visual	MS, TG	Space Plan (Tracking Suit Marker*39), Support Equipment (Yoga mat)	Embodied Avatar (Patient and therapist)
Jeon et al (2020) [47]	MS	–	Hip abduction and flexion, Knee flexion and extension	Camera (UNICARE)	PC	Visual Auditory	TG, BE	–	Embodied Avatar (Coach)
Tokuyama et al. (2019) [48]	MS	GM	Sitting in a chair to step on a virtual mole moving randomly	Camera (Kinect V1)	PC	Visual	TG, BE	Support Equipment (Chair)	Concrete Element (Moles)
Banaga et al (2022) [49]	B	S	Perform the assigned dance motions	IMU (XSens DOT)	VR headset (MR approach)	Visual Auditory	MS	–	Embodied Avatar (Patient)
Chen et al (2020) [50]	B	S	Perform goalkeeper's saving action	Camera (Kinect V2)	PC	Visual Auditory	MS, TG	Support Equipment (A-shaped suspension frame with safety belt)	Concrete Element (Soccer ball, avatar-goalkeeper)
Desai et al (2016) [51]	B	S	Performing the hip abduction exercise	Camera (Kinect V2)	TV	Visual	TG, BE	–	Concrete Element (Wooden plank, Beach, Lighthouse, Trees)

Table 1 (continued)

References	Rehabilitation Task			Interaction mode				Environmental elements	
	motor category [a]	Task theme [b]	Content	Input devices	Output devices	Sensory modality	Feedback information [c]	Physical	Virtual
Hoang et al (2016) [52]	B	GM	Step with a rhythm video	Mat built-in sensors	TV	Visual Auditory	TG, BE	Support Equipment (Stepping mat)	Abstract Element (Direction arrows)
Garrido et al (2013) [53]	B	-	Go from one initial point to the final one following a straight virtual line	Camera (Kinect V1)	PC	Visual Auditory	TG, BE	Space Plan (3 m long)	Abstract Element (Corrective arrows, Progress bar), Concrete Element (A common balance)

[a] *NWG* natural walking gait, *ST&OA* special trajectory and obstacle avoidance, *MS* muscle strength, *B* balance. [b] *S* sport, *SE* scenario exploration, *GM* game migration. [c] *MS* motion status, *TG* task guidance, *BE* background environment

for stepping tasks [30, 31], and to suspension systems for sports-themed activities [50].

Virtual environmental elements are categorized into three types: abstract elements, concrete elements, and embodied avatars, each playing a role in providing effective interactive feedback. Virtual content should be tailored to the scenario's requirements to enhance user engagement and task performance. Abstract elements utilize basic visual components to guide rehabilitation movements, including geometric shapes such as lines, surfaces, and bodies [29–31, 34, 35, 38]. These components also include interface symbols such as directional arrows [41, 42] and progress indicators [53] that guide and inform users during tasks. Concrete elements provide more tangible and contextually rich cues in the AR environment. Notable examples included virtual footprints for gait guidance [5, 55], and representations of natural elements such as plants, rivers, and birds [36, 37, 51], which have been demonstrated to subtly enhance the rehabilitation experience [56]. Embodied Avatars serve a variety of roles in delivering intuitive training guidance. These avatars can represent patients with enhanced performance capabilities [43, 46, 49], act as virtual coaches for action modeling [47], or serve as companions offering emotional encouragement and support [32]. A notable application was the introduction of an exoskeleton avatar, which visualized both the patient's intended motion (as represented by a motion intention avatar) [58] and the actual motion trajectory of the exoskeleton [57]. By displaying these elements side by side, the system enables patients to make timely adjustments to their lower-limb movements based on comparative feedback.

Key factors guiding the design of AR environment tailored for lower-limb rehabilitation

The design of AR environments for lower-limb rehabilitation requires careful consideration of both physical and virtual components to meet diverse therapeutic needs. Figure 3 presents a taxonomy of AR systems for lower-limb rehabilitation, highlighting two primary dimensions: rehabilitation tasks and interaction modes. Figure 2 provides a reference for identifying key environmental factors that contribute to engaging, context-appropriate, and personalized rehabilitation experiences.

Rehabilitation tasks performed in AR environment (RQ2-1)

To understand how AR environments were constructed and presented for rehabilitation, both the motor categories and task themes of the included studies were examined. First, rehabilitation tasks were classified based on the core lower-limb movements and postures targeted within AR settings. Simultaneously, tasks were categorized according to their thematic context to identify the most common training scenarios used to engage patients.

Motor category: Analysis revealed four primary lower limb motor categories: natural walking gait (NWG) (n =10), special trajectory and obstacle avoidance (ST&OA) (n =6), muscle strength (MS) (n =3), and balance (B) (n =5). Figure 4 illustrates representative examples of these categories. NWG and ST&OA tasks aim to practice everyday gait patterns and navigational skills; MS tasks focus on developing foundational strength necessary for mobility; and B tasks target improvements in postural stability. The following descriptions highlight the characteristics of these four motor categories, including the typical rehabilitation tasks and key physical and virtual elements integrated within the AR systems.

i) **Natural Walking Gait (NWG)**: Restoring a natural walking gait is a primary goal of lower-limb rehabilitation. AR environments commonly incorporated physical equipment such as treadmills [37] and instrumented floors [30] to facilitate gait training. However, notable differences between treadmill walking and overground walking [59] might limit the transfer of training effects to real-world contexts [24]. As an alternative, some systems used natural ground environments combined with virtual feedback projected directly onto the floor surface [40]. This approach enabled overground practice but may cause discomfort or instability if patients were required to look downward continuously during movement [36]. Another AR application visualized and guided gait for patients using assistive exoskeletons [29, 34]. In those cases, joint angle data from the exoskeleton were integrated into the AR system to provide real-time feedback on gait performance.

ii) *Special Trajectory and Obstacle Avoidance (ST&OA)*: Beyond basic gait training, many advanced tasks involved navigating special trajectories or avoiding obstacles. Physical obstacle courses posed safety risks and were often resource-intensive to implement, especially for patients with limited mobility. AR provided a safer and more adaptable alternative for ST&OA training by overlaying virtual pathways and obstacles onto the real world. For example, virtual circular pathways on the ground were used to improve turning ability in patients [44], and an AR hopscotch grid allowed for precise stepping practice [45]. Virtual obstacles such as approaching objects and simulated holes create interactive trajectories without exposing patients to real tripping hazards. Held et al. [41] developed an AR *parkour* scenario where patients stepped on virtual stones to cross a river and the scenario adjusted its difficulty (e.g., stone spacing) based on patient performance [40].

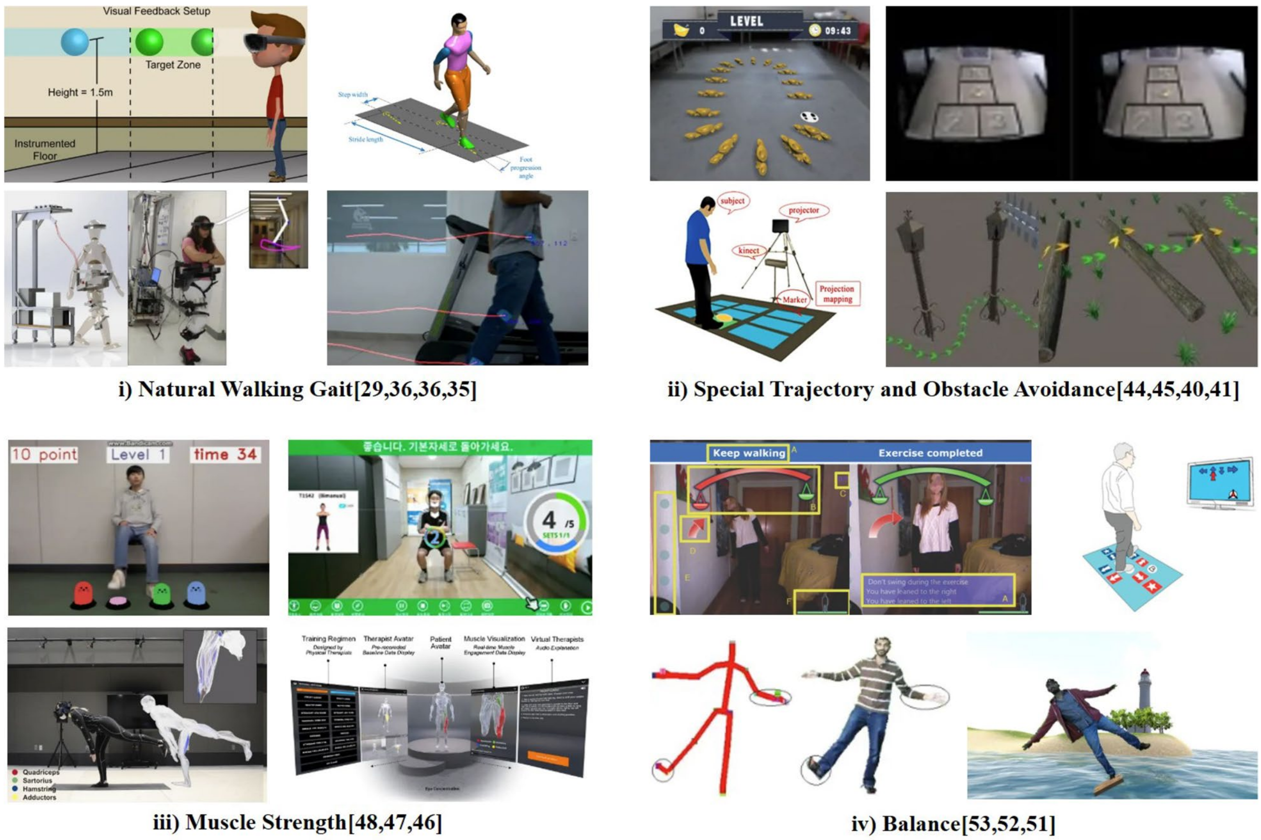

Fig. 4 Motor Categories in Existing Research

iii) *Muscle Strength (MS)*: Strengthening key muscle groups is essential during the early phase of rehabilitation, particularly for patients with severe lower-limb injuries, as sufficient muscle force is necessary to support walking exercises. This phase can be challenging due to pain [60] and decreased motivation [61]. AR systems enhanced patient self-efficacy during strength training [47] by providing visual feedback and motivational elements. To ensure correct muscle activation without continuous therapist supervision, some systems were combined with support tools (e.g., yoga mats [46] or chairs [48]) and sensors that detected muscle tension or activation levels [46]. For instance, visual overlays highlighted the specific muscle group intended for contraction, helping patients adjust their movements independently and accurately.

iv) *Balance (B)*: Balance training is essential for preventing falls and secondary injuries, particularly among older adults and individuals with lower-limb impairments. AR environments have been used to enhance engagement by guiding patients along straight or curved paths and visualizing progress in real time [53]. Janssen et al. [42] incorporated virtual targets for 180° turning, which adapted to real-time performance and supported patients in overcoming gait freezing episodes. Hoang et al. [52] combined AR with a sensory stepping mat to train directional stepping, thereby promoting accurate foot placement. Moreover, exercises that may be perceived as monotonous in traditional therapy (e.g., repeated hip abduction) have been transformed into engaging AR scenarios. For example, patients practiced balance by standing on a virtual surfboard or plank suspended over water [51], broadening their range of motion and enhancing motivation.

Task theme: More than half of the included studies (n =13) replicated conventional rehabilitation exercises in AR with minimal thematic variation, resulting in a relatively rigid integration of virtual elements. In contrast, the remaining studies employed creative task themes that more effectively integrated physical and virtual environments, enriching the user experience. Across all 25 studies, we identified three task-theme categories: sports(S) (n =3), scenario exploration (SE) (n =3) and game migration (GM) (n =5). Figure 5 presents representative examples of each category. The key features and representative cases of each task theme are described below.

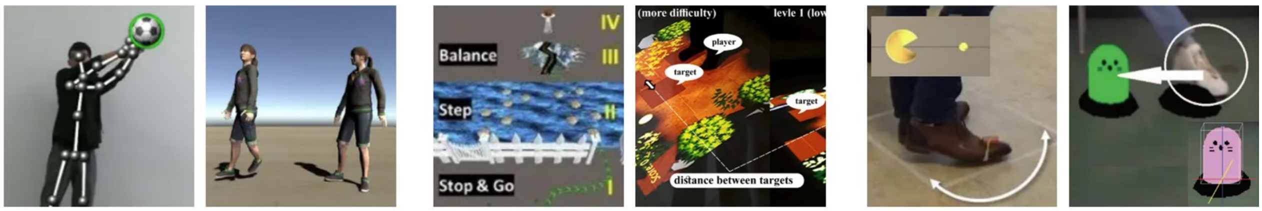

Fig. 5 Task Themes in Existing Research

i) Sports (S): Sports-themed AR scenarios create virtual versions of outdoor sports and games for rehabilitation. By assigning patients an active role in a sports context, these themes leverage natural body movements and the inherent motivational appeal of competition. For instance, Chen et al. [50] developed an AR stimulation of an open-air football game, in which patients acted as goalkeepers attempting to save virtual footballs arriving from various directions. The scenario included a virtual audience with cheering sounds effects to encourage participation and increase immersion. Desai et al. [51] created an AR exercise modeled on a water-based balance plank challenge, motivating patients to perform one-legged standing movements to maintain balance on a virtual plank. Similarly, Banaga et al. [49] developed a dance exergame in an AR setting for stroke rehabilitation, aiming to improve both cognitive and motor functions while fostering a sense of control even within confined spaces.

ii) *Scenario Exploration (SE)*: These themes encourage patients to interact with the AR environment in an exploratory and open-ended manner, offering a personalized and immersive experience. Held et al. [41] constructed a *forest-themed parkour adventure* in AR, in which users followed continuously appearing arrows to navigate tasks such as crossing jungle branches and weaving through streetlights. Wang et al. [44] designed an AR scenario called "*Treasure Island Adventure*" for elderly patients with Parkinson's disease. In this scenario, users followed a trail of virtual gold ingots to collect treasures while avoiding traps, helping patients feel confident attempting movements they previously considered potentially dangerous. Amiri et al. [40] developed a garden exploration scenario using spatial projection mapping, where patients interacted with location-specific bricks to reveal flowers and vegetation, thereby enhancing engagement compared to the typical Square-Stepping Exercise.

iii) *Game Migration (GM)*: This approach extracts elements from popular games and integrates them into rehabilitation, effectively "gamifying" [62] the exercises to boost engagement and reduce cognitive load for patients. Tokuyama et al. [48] migrated the *whack-A-Mole* game into an AR environment for lower-limb strength training, using Microsoft Kinect to guide users in stepping motions that interacted with the game. Janssen et al. [42] incorporated elements of *Pac-Man* into an AR turning exercise, in which patients followed virtual pellets (dots) to practice 180° turns, with mixed results on turn-speed improvement. Hoang et al. [52] adapted arcade dance machine mechanics for balance training in older adults, using directional arrow cues and rhythmic music to increase motivation and deliver immediate performance feedback.

Interaction modes provided by AR environments (RQ2-2)

In AR environments designed for lower-limb rehabilitation, interaction modes are pivotal for creating an immersive and responsive experience, and focus on two types of touchpoints: information input and output. Input touchpoints are facilitated by monitoring sensors that capture key user data, such as movement patterns or physiological signals. Conversely, output touchpoints deliver feedback through multiple sensory modalities. Based on the included 25 papers, we systematically analyzed how current AR systems implement these touchpoints and how information flows between them. We also explored potential interaction modes enabled by emerging technologies. Figure 6 illustrates these interaction touchpoints, with a particular focus on the integration of assistive devices such as exoskeletons within the AR rehabilitation framework.

INPUT: monitoring touchpoints

To explore the interaction possibilities between patients and the AR environment, we first examined the input mechanisms. AR systems in the reviewed studies supported a diverse array of sensors [63, 64], providing various monitoring touchpoints that captured distinct aspects of body movement during rehabilitation. These monitoring touchpoints were classified into five main types: camera-based ($n = 15$), electrical signals ($n = 2$), wearable-device embedded ($n = 2$), body-attached motion sensors ($n = 8$), and plantar pressure sensors (n

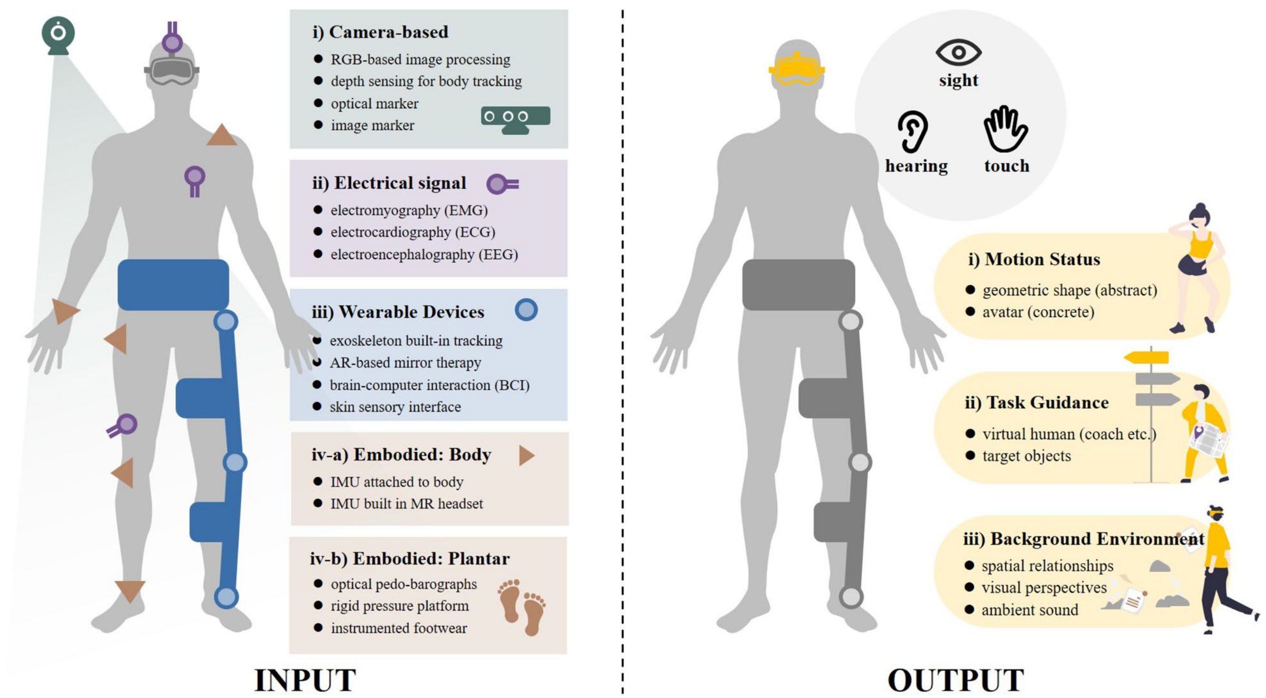

Fig. 6 Input and Output Touchpoints in the AR-based Lower-Limb Rehabilitation System

=2) (see Fig. 6, left). The following subsections describe each type of monitoring touchpoint used in AR settings.

i) *Camera-based touchpoints*: These utilized optical sensors such as RGB or depth cameras to track overall posture and limb trajectories. The Microsoft Kinect (V1 or V2) was the most frequently employed camera in current research [37, 40, 43, 45, 48, 50, 51, 53], offering reliable markerless motion capture via its RGB camera and infrared depth sensor.

ii) *Electrical signal monitoring touchpoints*: These systems monitored physiological parameters in real-time during rehabilitation training. Among the common signals, electromyography (EMG), electrocardiogram (ECG), and electroencephalogram (EEG), EEG has emerged as a novel method to capture a patient's motor intentions directly from brain activity. Several studies have integrated EEG cap devices to monitor patients' movement intentions or mental engagement, effectively incorporating a brain–computer interface into the AR rehabilitation system [29, 33].

iii) *Wearable devices-built-in touchpoints*: Sensors embedded in wearable rehabilitation devices, such as robotic exoskeletons, provided another input modality. These touchpoints can automatically monitor and even adjusted training exercises, representing a new paradigm of device-assisted rehabilitation [65, 66]. For example, sensors installed at joints or pressure points of a lower-limb exoskeleton can record joint angles, forces, and torques [34], thereby enabling the AR system to adapt feedback in real time as the exoskeleton moved through rehabilitation exercises.

Beyond these conventional interaction modes of monitoring and feedback modes, several studies have explored innovative interaction modes enabled by emerging technologies, opening new avenues for engaging rehabilitation practices. Examples include enhanced mirror therapy, brain-computer interfaces, and skin-based sensory feedback:

- *Mirror Therapy in AR*: Conventional mirror therapy reflects movements of the healthy limb to create the illusion that the affected limb is functioning normally [67]. In contrast, AR provides novel enhancements to mirror therapy. Unberath et al. [68] combined a physical mirror with an HMD-based AR system to stabilize limbs and allow observation of static movements, thereby creating new opportunities for cortical reorganization and improved functional mobility. Similarly, Desai et al. [51] employed avatars in an AR environment to replicate real-time rehabilitation movements, enabling patients to engage in more dynamic tasks and fostering a greater sense of achievement.
- *Brain-Computer Interface (BCI)*: BCIs integrate hardware and software to translate neural activity into system commands [69]. Wang et al. [29] proposed a

portable steady-state visual evoked potential-based BCI (SSVEP-BCI) system specifically designed for use within AR rehabilitation exoskeletons. Unlike traditional BCIs that rely on stationary screen-based stimuli, AR HMDs can provide real-time visual feedback directly aligned with patient movement, facilitating novel active–passive hybrid training modes.

- *Skin Sensory Interface*: Many AR applications depend on HMD for visual and auditory feedback, but the bulk and discomfort associated with prolonged use pose challenges, especially for individuals with lower-limb injuries [70]. Advances in nanomaterials and flexible wearable sensors, including those for pressure, strain, acoustic and physiological signals (e.g., electrooculography – EOG and EEG), pave the way for lighter, more comfortable haptic input methods. Soft AR contact lenses and actuators capable of delivering force, thermal, and vibrational feedback introduce innovative skin sensory interfaces (e-skin), thereby enhancing the user experience through novel output modalities [71].

iv) *Embodied Touchpoints*: Inertial and pressure sensors attached to the patient's body also serve as "embodied" monitoring touchpoints.

- *Inertial Measurement Units (IMU)*: Positioned on various body segments, IMUs capture real-time acceleration data, thereby facilitating the collection of kinematic information such as velocity and displacement. Commercial IMU products are lightweight, modular, and cost-effective, allowing their widespread application across diverse research initiatives [41, 42]. In addition, some AR HMDs (e.g., HoloLens) also have built-in IMU modules to monitor both head movements and body posture in conjunction with gait analysis algorithms [38].
- *Plantar Touchpoints*: These sensors monitor the interaction between the feet of individuals with lower-limb injuries and the ground or exoskeletal plantar attachments. Utilizing array pressure-sensing sensors [30, 31], these touchpoints record motion data, including plantar pressure distribution and center of gravity shifts, which are essential for tailoring rehabilitation feedback to individual gait patterns.

OUTPUT: feedback touchpoints

This section examines the output mechanisms of AR environments, with a specific focus on feedback touchpoints, as analyzed across the 25 included studies. AR environments are capable of delivering various forms of augmented feedback to patients. Most studies employed MR or VR headset devices (n =13), followed by video streams on computer or TV screens (n =6), and spatial projections (n =4). Feedback content was typically categorized into three types: motion status (MS) (n =10), task guidance (TG) (n =20) and background environment (BE) (n =14) (see Fig. 6—right). The following sections describe how each category was implemented in AR environments for lower-limb rehabilitation:

i) *Motion Status*: Real-time feedback on motion status is critical for helping patients verify and correct their movements during rehabilitation. AR environments have facilitated this by enabling patients to intuitively understand and verify the accuracy of their training movements. Existing studies have often utilized abstract elements or concrete avatars to visualize the motion status, where changes in the size and color of geometric shapes such as circles [31], spheres [30], and cylinders [50] indicate variations in walking speed and posture, aiding patients in adjusting their walking rhythm and speed. For instance, Hurtado et al. [35] reflected real-time movement of three primary joints of the lower limb (hip, knee, and ankle) via three distinct cubes. Hidayah et al. [34] depicted the full trajectory lines of a patient's foot points through a gait cycle. Zhu et al. [46] visualized the real-time status of key muscle groups in the lower limbs using a virtual body with translucent muscle tissues, where variations in color intensity revealed the force exerted by each group, aiding patients in recognizing proper muscle activation and minimizing the risk of secondary injuries. Furthermore, Banaga et al. [49] simplified task execution by having patients perform basic movements, with more complex motor activities represented by energetic avatars, thereby enhancing motor feedback and bolstering the patient's sense of control over the body. Luchetti et al. [43] constructed a 2D avatar with transparency that can adapt to both first-person and third-person perspectives, offering versatile perspectives for understanding and performing rehabilitation exercises.

ii) *Task Guidance*: Task guidance provides instructional support for patients as they perform rehabilitation tasks [72]. Many studies have employed virtual coaches or target objects to demonstrate step-by-step movements. Jeon et al. [47] used multi-angle videos of a virtual coach, presented from both frontal and lateral perspectives within the AR environment, to provide intuitive guidance. Miller et al. [32] introduced a realistic walking avatar, positioned ahead of the patient within an HMD-based AR setting. This design leveraged patients' natural tendency to synchronize their pace with a walking partner, thereby encouraging coordinated movement patterns [55].

Bennour et al. [36] displayed virtual footprints overlaid on the ground to visualize gait parameters such as stride length, stride width, and stride speed. To distinguish movements between left and right limbs, contrasting colors (e.g., red and blue) were used [43, 52], offering more personalized visual cues for bilateral coordination. Wang et al. [44] incorporated virtual cave obstacles into the real-world ground plane, aligning visual elements with users' cognitive expectations and increasing task engagement. Tokuyama et al. [48] enhanced interactivity by embedding a game-like mechanic in which virtual moles randomly appeared and disappeared, promoting sustained attention throughout the rehabilitation session. Garrido et al. [53] used a virtual balance board to support task guidance, enabling patients to visually assess and adjust their balance, simplifying the concept of balance control.

iii) *Background Environment*: The background environment provides the contextual and sensory setting for AR-based rehabilitation. Analysis of the 25 included studies highlights three key components: spatial relations, observational perspectives, and ambient sound, as integral to establishing a cohesive and immersive AR experience. These elements support seamless integration between physical and virtual worlds, thereby enhancing the overall rehabilitation process.

- *Spatial Relation*: Alignment between physical and virtual spaces is essential in AR environments. Traditional rehabilitation exercises often use horizontal stripes on the floor as navigational aids. Ahn et al. [38] designed these lines with a perspective setting that changes with distance. Virtual elements can be anchored in the environment as either world-locked (environment-relative) or body-locked (user-attached). Guinet et al. [31] noted that body-locked anchors can disrupt task performance due to their variability. Improper overlap or occlusion between virtual elements and the user's body can disrupt accurate spatial perception. To address this, Sekhavat et al. [37] added virtual contour lines around the edges of the feet, thereby preventing footprint–body occlusion.
- *Observation Perspective*: Viewing perspective plays a key role in accurately presenting lower-limb movements, yet is often underemphasized. Hurtado et al. [35] demonstrated that side, frontal, and overhead perspectives are effective for visualizing joint trajectories. Luchetti et al. [43] implemented a third-person view combining frontal and overhead angles, which enhanced patients' perception of their movement patterns and spatial orientation.
- *Ambient sounds*: Auditory cues enrich the sensory experience and contribute to engagement and motivation during rehabilitation. Held et al. [41] incorporated natural sounds, such as bird calls triggered by knee movements, to provide encouraging feedback. Ko et al. [33] implemented collision sounds in virtual object interactions to enhance immersion. Amiri et al. [40] used dynamic sound cues to guide movements, distinguish correct from incorrect actions, and indicate progress by adjusting background audio, thereby reinforcing user motivation.

Discussion

The aim of this review was to optimize the design of the AR environment for lower-limb rehabilitation by systematically mapping the available literature on the use of AR environments by individuals with lower-limb disabilities. Our findings highlight the significant advancements that AR environments offer in the field of rehabilitation, particularly in enhancing patient engagement and improving outcomes. Through the analysis of existing AR systems, this study presents a comprehensive framework that integrates motor categories, task themes, physical and virtual environmental elements, and monitoring and feedback touchpoints, as shown in Fig. 7.

Building on these insights, we have identified key elements that are crucial for effective AR environment design in lower-limb rehabilitation. The integration of physical and virtual environmental elements is central to enhancing rehabilitation motivation and efficiency. Additionally, specifying rehabilitation tasks and embedding them in immersive thematic scenarios can significantly improve user engagement. The strategic use of interaction and feedback touchpoints ensures comprehensive support throughout the rehabilitation process, fostering both motivation and control. These findings lay a foundation for advancing AR-based rehabilitation systems with a focus on personalized and engaging patient interventions.

Customization and progression in AR rehabilitation environment

AR environments offer distinct advantages over traditional rehabilitation settings by dynamically adapting task designs in response to a patient's rehabilitation progress (e.g., progressing from *natural walking gait* to *special trajectory* and *obstacle avoidance* to *balance*). This capability enables low-cost and convenient personalized adjustments, thereby sustaining patient engagement throughout the rehabilitation process. An ideal AR environment should cater to diverse motor categories and rehabilitation stages, offering customizable themes based on patient preferences. As patients recover, task difficulty should increase accordingly, for example, starting with muscle strengthening and basic gait, then advancing to

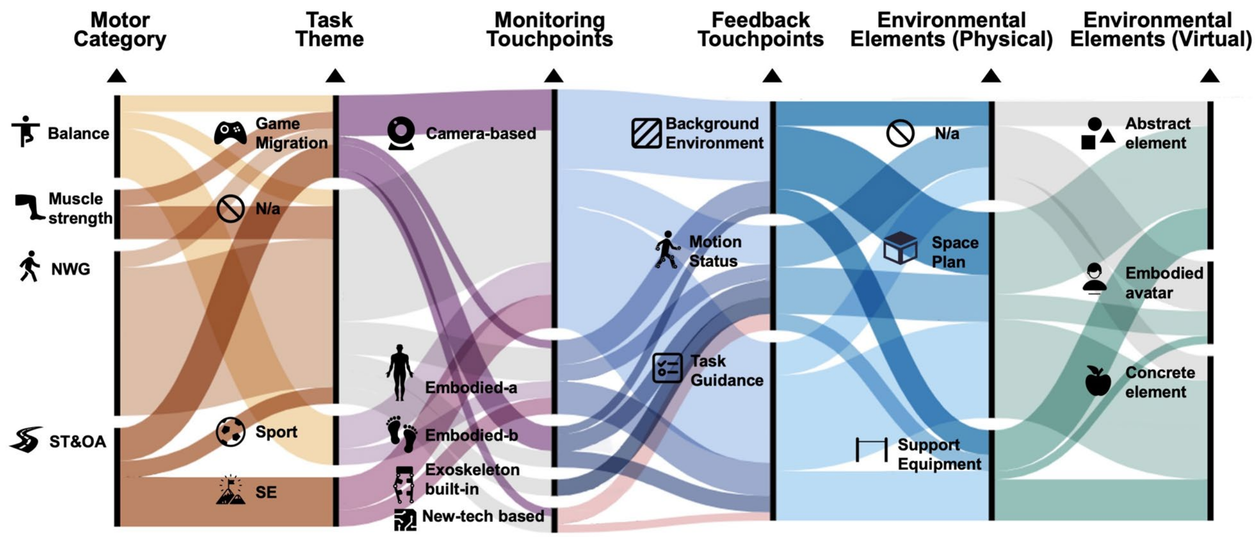

Fig. 7 Sankey Diagram of Results

complex trajectories and obstacle avoidance, and eventually incorporating balance-challenging activities.

Unlike traditional rehabilitation settings, which primarily focus on creating a therapeutic atmosphere through the harmonized arrangement of physical facilities such as lights, colors, paintings, and music [54], AR environments present a cost-effective and flexible alternative that supports seamless transitions between various rehabilitation tasks [73].

Optimizing interaction with AR devices in rehabilitation environments

The choice of interaction hardware in an AR environment (whether mobile handheld devices,

or spatial projectors) can be tailored to the specific training scenario to maximize efficiency and immersion. Each mode of interaction hardware has strengths and weaknesses: for instance, HMDs provide an immersive experience but can burden the user's head and may cause discomfort over long sessions [74, 75], whereas spatial projectors enable larger environments but require sufficient space and proper lighting conditions. Moreover, most AR systems in these studies activated a relatively homogeneous set of sensory modalities (primarily visual, sometimes auditory), indicating opportunities to enrich the sensory experience.

To address these issues, researchers have proposed a number of innovative solutions. One approach is an AR application pipeline for monitoring and controlling Internet of Things (IoT) devices in indoor environments, which can be deployed on common AR platforms including smartphones, tablets and glasses [76]. This expands the reach of AR rehabilitation by integrating with smart home equipment and sensors. Another development is portable AR projection technology that increases flexibility in where AR rehab can be delivered [77]. Moreover, advanced pose-tracking techniques with corresponding visual cues have been introduced to create AR-enhanced workout environments [78]. A further innovation is software systems for AR environmental design that integrate point cloud capture and editing, offering new possibilities for interactive and immersive rehabilitation scenarios [79]. These approaches could mitigate current hardware limitations, significantly improving the range and usability of AR interaction modes as well as the overall user experience in rehabilitation.

In addition to technical challenges, practical limitations of AR hardware also merit consideration. The high cost of advanced AR systems and their limited accessibility in both clinical and home settings may hinder widespread adoption. Real-world deployment also requires robust tracking and precise spatial calibration, which complicate implementation outside controlled environments. Future research should not only pursue technical improvements but also evaluate the economic viability of AR solutions and how they can be integrated into existing rehabilitation infrastructures. In other words, demonstrating cost-effectiveness and ease of incorporation into therapy workflows will be key for AR rehabilitation technologies to transition from the lab to routine practice.

Supporting multi-sensory modalities in AR environment

Integrating a range of sensory modalities (visual, audio, and haptic) is crucial for enhancing rehabilitation efficiency and user experience in AR environments [75] [77] [78]. There is a growing need to explore tactile interaction experiences that combine emerging rehabilitation technologies with AR [79] [80] [81]. Exoskeletons present a promising opportunity to incorporate tactile sensory feedback, although current software and hardware limitations pose challenges.

Nonetheless, incorporating haptic feedback into AR training could significantly enhance training outcomes. Specifically, using the inherent touchpoints between a wearable exoskeleton and the human body to deliver force or vibration cues is highly recommended [87]. By feeling pressure or vibrations at key points (for example, where an exoskeleton contacts the legs), patients can better understand their movement and balance, thereby complementing visual and auditory cues. Several studies have begun to address this challenge by using plantar pressure sensors to detect weight distribution and vibration modules to cue users during gait training [85, 86]. The forces and motions exchanged between the human lower limbs and an exoskeleton provide a natural source of tactile information that AR systems can exploit by synchronizing haptic signals with visual overlays and sound cues, creating a fully immersive feedback loop. For example, Hidayah et al. [34] demonstrated that HMD-based AR devices can present real-time motion trajectories of leg joints, assisting patients wearing exoskeletons in monitoring their performance. Future research should investigate exoskeleton-based haptic interaction touchpoints and develop inclusive interaction modes for multi-terminal AR devices in rehabilitation settings.

Integration of exoskeletons into AR rehabilitation Environments.

Current research on lower-limb exoskeleton-assisted AR rehabilitation remains in its early stages, warranting a thorough exploration of rehabilitation mechanisms and processes. Lower-limb robotic exoskeletons are generally designed to support a single style of natural walking gait motion, including treadmill-based and overground walking formats [88]. However, comprehensive rehabilitation must address a spectrum of activities: muscle strengthening in the early phase, nonlinear trajectory and obstacle avoidance in intermediate phases, and combined balance training to prevent falls in later phases [89]. These components are noticeably absent from existing exoskeleton-assisted AR systems, indicating significant opportunities for innovative design of wearable exoskeleton functions rather than relying on treadmills or suspension systems. By delivering rehabilitation tasks that gradually increase in difficulty according to a patient's recovery, exoskeleton-assisted AR environments could facilitate patients' transition from bed-rest to unassisted daily activities.

To broaden accessibility and inclusivity for a diverse group of users, including exoskeleton wearers, and providing tactile compensation for the deafblind community. It is vital to design inclusive interaction modes for multi-terminal AR devices. Investigating exoskeleton-based haptic interaction touchpoints could significantly boost user engagement and motivation during rehabilitation exercises.

Furthermore, given the complexity inherent in integrating AR with robotic exoskeletons, addressing technical challenges in software system development and control remains a critical area for future research. This effort should include exploring the integration of platforms such as the Robot Operating System (ROS) with Unity to enhance overall system functionality.

Comparing lower-limb and upper-limb rehabilitation in AR environments

The results highlight a distinction between lower-limb and upper-limb rehabilitation tasks, with lower-limb procedures being unilaterally specific and demanding a larger environmental interaction space. Consequently, environmental elements play a greater role in lower-limb rehabilitation compared to upper-limb procedures. In upper-limb rehabilitation, AR systems typically focus on one limb [90], and exercises can often be mirrored relatively easily to the unaffected side. By contrast, effective lower-limb rehabilitation must restore the function of the affected leg while accounting for the coordinated movement of the other leg. For example, a patient with hemiplegia may require targeted AR training for the impaired leg that also involves stepping or balance exercises with the healthy leg. This complexity means more sophisticated and adaptable AR setups are needed for lower limbs [24, 91]. Consequently, developing AR environments that accommodate such bilateral coordination is a promising direction for future research.

In addition, upper-limb rehabilitation typically operates within a confined area (often at a table or within arm's reach) [92], whereas lower-limb rehabilitation involves broader spatial interactions (moving around a room or walking a certain distance). This places greater demands on synchronizing virtual content with the physical environment for lower-limb AR applications. Properly aligning AR feedback with real-world surfaces (floors, obstacles, etc.) can improve patient acceptance and enthusiasm for training [93]. While some studies have explored AR environments for upper-limb rehab using tabletop games [94] and hand-focused haptic devices [95], designing effective AR environments for lower limbs requires more innovative approaches that integrate virtual scenes with interactions spanning the entire room and the patient's body. The systematic framework presented in this review provides valuable guidance for addressing these unique challenges by leveraging both physical and virtual environment elements in tandem.

Limitations of this review

This scoping review has several limitations. First, our search was limited to English-language, peer-reviewed journals and did not capture gray literature, conference proceedings, or clinical case reports, which may have omitted relevant AR rehabilitation applications. Future reviews could expand the search to include conference proceedings, technical reports, and clinical case studies to capture a broader spectrum of AR-based rehabilitation research. Second, the 25 included studies exhibited a small average sample size (mean approximately 20 participants; range 3–109) and limited demographic diversity, with most enrolling younger to middle-aged adults and minimal representation of older adults (> 65 years) or other underrepresented groups, thus constraining the generalizability of our findings. These studies also varied widely in intervention protocols, outcome measures, and follow-up durations (2–12 weeks), precluding any quantitative synthesis. Third, nearly all interventions were conducted in controlled laboratory environments, with only one in a clinical setting and none in home-based or community contexts, so the long-term feasibility and durability of AR-induced gains remain unclear. Finally, we did not systematically assess hardware usability, cost-effectiveness, or integration into routine practice, practical factors that will be critical for real-world adoption. Future work should address these gaps by standardizing metrics, diversifying study settings and populations, extending follow-up periods, and evaluating economic and usability aspects of AR interventions.

Conclusion

This scoping review presents a comprehensive overview of AR environments in lower-limb physical rehabilitation, emphasizing the importance of both rehabilitation tasks and interaction modes in system design. The taxonomy illustrated in Fig. 3 identifies key physical and virtual environmental elements that are integral to AR-based lower-limb rehabilitation. Our findings underscore the potential of AR environments to enhance the effectiveness of training and enrich the overall rehabilitation experience. We recommend broadening the application of AR environments across all rehabilitation stages and motor categories by integrating diverse monitoring and feedback touchpoints and prioritizing multisensory interactions, especially those involving exoskeleton-based haptic feedback. The proposed framework in Fig. 2, along with insights from this review, provides a practical guide for selecting and combining environmental elements to create engaging and effective AR rehabilitation programs.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-025-01643-7.

Additional file1

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Author contributions

Y.L. conceived the study and acquired funding. Y.L. and Q.Z. were responsible for the literature search and data extraction. All authors contributed to data analysis and conflict resolution, drafted the manuscript, and reviewed and approved the final version of the paper.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

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Competing interests

The authors declare no competing interests.

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References

1. WHO. Rehabilitation [Internet]. World Health Organisation. World Health Organization: WHO; 2024. https://www.who.int/news-room/fact-sheets/detail/rehabilitation
2. Rodríguez-Fernández A, Lobo-Prat J, Font-Llagunes JM. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J NeuroEng Rehabilitation. 2021;18(1):22.
3. Bezner JR. Promoting health and wellness: Implications for physical therapist practice. Phys Ther. 2015;95(10):1433–44.
4. Yeh SC, Chang SM, Chen SY, Hwang WY, Huang TC, Tsai TL. A lower limb fracture postoperative-guided interactive rehabilitation training system and its effectiveness analysis. 2012 IEEE 14th International Conference on e-Health Networking, Applications and Services (Healthcom). 2012; 12:149–54.
5. Cosio LD, Buruk O 'Oz', Fernández Galeote D, Bosman IDV, Hamari J. Virtual and Augmented Reality for Environmental Sustainability: A Systematic Review. Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. 2023;6(23).
6. Fu Y, Hu Y, Sundstedt V. A systematic literature review of virtual, augmented, and mixed reality game applications in healthcare. ACM Transact Comput Healthcare. 2022;3(2):1–27.

7. Yeung AWK, Tosevska A, Klager E, Eibensteiner F, Laxar D, Stoyanov J, et al. Virtual and augmented reality applications in medicine: Analysis of the scientific literature. J Med Internet Res. 2021;23(2): e25499.
8. Howard MC, Davis MM. A meta-analysis and systematic literature review of mixed reality rehabilitation programs: Investigating design characteristics of augmented reality and augmented virtuality. Comput Hum Behav. 2022;130: 107197.
9. Namazi N, Khani Y, Salmannezhad A, Behdadfard M, Safaee E, Nouroozi M, et al. Virtual and augmented reality for anxiety reduction in orthopedic patients and providers: a systematic review. J Orthop Surg Res. 2025. https://doi.org/10.1186/s13018-025-05846-5.
10. Cho H, Park S, Park C, Jung SU. Efficient Mapping Technique under Various Spatial Changes for SLAM-based AR Services. Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology. 2021;1–3.
11. Krauß V, Boden A, Oppermann L, Reiners R. Current Practices, Challenges, and Design Implications for Collaborative AR/VR Application Development. Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. 2021;454(15).
12. Kylén M, Ytterberg C, Koch L, Elf M. How is the environment integrated into post-stroke rehabilitation? A qualitative study among community-dwelling persons with stroke who receive home rehabilitation in Sweden. Health Soc Care Commun. 2021;30(5):1933–43.
13. Shi L, Li B, Kim C, Kellnhofer P, Matusik W. Towards real-time photorealistic 3D holography with deep neural networks. Nature. 2021;591(7849):234–9.
14. Qi W, Sun S, Niu T, Zhao D. Research and prospects of virtual reality systems applying exoskeleton technology. Univ Access Inf Soc. 2022;23(1):119–40.
15. Gorman C, Gustafsson L. The use of augmented reality for rehabilitation after stroke: a narrative review. Disability and Rehabilitation: Assistive Technology. 2020;17(4):409-417.
16. Ramírez ER, Petrie R, Chan K, Signal N. A tangible interface and augmented reality game for facilitating sit-to-stand exercises for stroke rehabilitation. Proceedings of the 8th International Conference on the Internet of Things. 2018;28(4).
17. Patil V, Narayan J, Sandhu K, Dwivedy SK. Integration of Virtual Reality and Augmented Reality in Physical Rehabilitation: A State-of-the-Art Review. Revolutions in Product Design for Healthcare. 2022;177–205.
18. Mubin O, Alnajjar F, Jishtu N, Alsinglawi B, Al MA. Exoskeletons with virtual reality, augmented reality, and gamification for stroke patients' rehabilitation: Systematic review. JMIR Rehabilitation Assistive Technol. 2019;6(2): e12010.
19. Suzuki R, Karim A, Xia T, Hedayati H, Marquardt N. Augmented Reality and Robotics: A Survey and Taxonomy for AR-enhanced Human-Robot Interaction and Robotic Interfaces. Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 2022;553(33).
20. Toledo-Peral CL, Vega-Martínez G, Mercado-Gutiérrez JA, Rodríguez-Reyes G, Vera-Hernández A, Leija-Salas L, et al. Virtual/augmented reality for rehabilitation applications using electromyography as control/biofeedback: Systematic literature review. Electronics. 2022;11(14):2271.
21. Khokale R, Mathew GS, Ahmed S, Maheen S, Fawad M, Bandaru P, et al. Virtual and Augmented Reality in Post-stroke Rehabilitation: A Narrative Review. Cureus. 2023. https://doi.org/10.7759/cureus.37559.
22. Sukran Karaosmanoglu, Cmentowski S, Nacke LE, Steinicke F. Born to Run, Programmed to Play: Mapping the Extended Reality Exergames Landscape. arXiv (Cornell University). 2024;1–28.
23. Taufiq M, Wicaksono DW. Efficacy Comparison of Augmented Reality and Virtual Reality-based Games for Post-Stroke Rehabilitation: A Systematic Literature Review. 2023 9th International HCI and UX Conference in Indonesia (CHIuXiD). 2023;53–8.
24. Cmentowski S, Karaosmanoglu S, Nacke LE, Steinicke F, Krüger J. Never skip leg day again: Training the lower body with vertical jumps in a virtual reality exergame. arXiv (Cornell University). 2023;786:18.
25. Leong SC, Tang YM, Toh FM, Fong KNK. Examining the effectiveness of virtual, augmented, and mixed reality (VAMR) therapy for upper limb recovery and activities of daily living in stroke patients: a systematic review and meta-analysis. J NeuroEng Rehabilitation. 2022;19(1):93.
26. Roever L. PICO: Model for clinical questions. Evid Based Med Pract. 2018;3(2):1–2.
27. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. Ann Intern Med. 2018;169(7):467–73.
28. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. Int J Soc Res Methodol. 2005;8(1):19–32.
29. Wang F, Wen Y, Bi J, Li H, Sun J. A portable SSVEP-BCI system for rehabilitation exoskeleton in augmented reality environment. Biomed Signal Process Control. 2023;83:104664–74.
30. Evans E, Dass M, Muter WM, Tuthill C, Tan AQ, Trumbower RD. A wearable mixed reality platform to augment overground walking: a feasibility study. Front Human Neurosci. 2022;16:868074.
31. Guinet AL, Bouyer G, Otmane S, Desailly E. Visual feedback in augmented reality to walk at predefined speed cross-sectional study including children with cerebral palsy. IEEE Trans Neural Syst Rehabil Eng. 2022;30:2322–31.
32. Miller DAL, Ogata T, Sasabe G, Shan L, Tsumura N, Miyake Y. Spatiotemporal gait guidance using audiovisual cues of synchronized walking avatar in augmented reality. IEEE Access. 2022;10:90498–506.
33. Ko LW, Stevenson C, Chang WC, Yu KH, Chi K, Chen Y, et al. Integrated gait triggered mixed reality and neurophysiological monitoring as a framework for next-generation ambulatory stroke rehabilitation. IEEE Trans Neural Syst Rehabil Eng. 2021;29:2435–44.
34. Hidayah R, Chamarthy S, Shah A, Fitzgerald-Maguire M, Agrawal SK. Walking with augmented reality: A preliminary assessment of visual feedback with a cable-driven active leg exoskeleton (C-ALEX). IEEE Robot Automation Lett. 2019;4(4):3948–54.
35. Hurtado J, Saint-Priest Y, Caicedo E. Development of a gait recognition visualization system using augmented reality. Int Conf Virtual Reality Visualization (ICVRV). 2019;2019:196–9.
36. Bennour S, Ulrich B, Legrand T, Jolles BM, Favre J. A gait retraining system using augmented-reality to modify footprint parameters: Effects on lower-limb sagittal-plane kinematics. J Biomech. 2018;66:26–35.
37. Sekhavat YA, Namani MS. Projection-based AR: Effective visual feedback in gait rehabilitation. IEEE Transact Human-Mach Syst. 2018;48(6):626–36.
38. Ahn D, Chung H, Lee HW, Kang K, Ko PW, Kim NS, et al. Smart gait-aid glasses for parkinson's disease patients. IEEE Trans Biomed Eng. 2017;64(10):2394–402.
39. Pinto-Fernandez D, Gomez M, Rodrigues C, Rojo A, Raya R, Rocon E, et al. Augmented Reality Feedback for Exoskeleton-Assisted Walking. A Feasibility Study. IEEE International Conference on Rehabilitation Robotics. 2023;1–6.
40. Amiri Z, Sekhavat YA, Goljaryan S. StepAR: A personalized exergame for people with multiple sclerosis based on video-mapping. Entertain Comput. 2022;42: 100487.
41. Held JPO, Yu K, Pyles C, Veerbeek JM, Bork F, Heining SM, et al. Augmented reality-based rehabilitation of gait impairments: Case report. JMIR Mhealth Uhealth. 2020;8(5): e17804.
42. Janssen S, de Ruyter J, van Steveninck HS, Salim HM, Cockx BR, Bloem THeida, et al. The effects of augmented reality visual cues on turning in place in parkinson's disease patients with freezing of gait. Front Neurol. 2020;11:185.
43. Luchetti A, Parolin E, Butaslac I, Fujimoto Y, Kanbara M, Bosetti P, et al. Stepping over Obstacles with Augmented Reality based on Visual Exproprioception. 2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). 2020;96–101.
44. Wang Y, Chen CH, Lin YC. Balance Rehabilitation System for Parkinson's Disease Patients based on Augmented Reality. 2020 IEEE Eurasia Conference on IOT, Communication and Engineering (ECICE). 2020;191–4.
45. Chessa M, Solari F. Walking in Augmented Reality: An Experimental Evaluation by Playing with a Virtual Hopscotch. 2017 IEEE International Symposium on Mixed and Augmented Reality. 2017; 6:143–8.
46. Zhu J, Lei Y, Shah A, Schein G, Ghaednia H, Schwab J, et al. MuscleRehab: Improving Unsupervised Physical Rehabilitation by Monitoring and Visualizing Muscle Engagement. DSpace@MIT (Massachusetts Institute of Technology). 2022;1–14.
47. Jeon S, Kim J. Effects of augmented-reality-based exercise on muscle parameters, physical performance, and exercise self-efficacy for older adults. Int J Environ Res Public Health. 2020;17(9):3260.
48. Tokuyama Y, Rajapakse RPCJ, Yamabe S, Konno K, Hung YP. A kinect-based augmented reality game for lower limb exercise. Int Conf Cyberworlds (CW). 2019;2019:399–402.
49. Banaga SG, O'Sullivan C. Stroke Rehabilitation through Proxy Agency and Embodiment in Mixed Reality. 2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). 2022; 22:964–7.

50. Chen S, Hu B, Gao Y, Liao Z, Li J, Hao A. Lower limb balance rehabilitation of post-stroke patients using an evaluating and training combined augmented reality system. IEEE Int Symposium Mixed Augmented Reality Adjunct. 2020;2020:217–8.
51. Desai K, Bahirat K, Ramalingam S, Prabhakaran B, Annaswamy T, Makris UE. Augmented reality-based exergames for rehabilitation. Proceedings of the 7th International Conference on Multimedia Systems. 2016;1–10.
52. Hoang P, Schoene D, Gandevia S, Smith S, Lord SR. Effects of a home-based step training programme on balance, stepping, cognition and functional performance in people with multiple sclerosis – a randomized controlled trial. Mult Scler J. 2015;22(1):94–103.
53. Enrique J, Penichet VR, Lozano Ma, Marset I. Balance Disorder Rehabilitation through Movement Interaction. Proceedings of the ICTs for improving Patients Rehabilitation Research Techniques. 2013;252368.
54. Huisman ERCM, Morales E, van Hoof J, Kort HSM. Healing environment: A review of the impact of physical environmental factors on users. Build Environ. 2012;58(58):70–80.
55. Zivotofsky AZ, Hausdorff JM. The sensory feedback mechanisms enabling couples to walk synchronously: An initial investigation. J Neuroeng Rehabil. 2007;4:28.
56. Van AE, Foundation 200 Years University Hospital Groningen. Health impacts of healing environments: a review of evidence for benefits of nature, daylight, fresh air, and quiet in healthcare settings. Groningen: Foundation 200 Years University Hospital Groningen; 2005.
57. Emanuele Ruffaldi, Barsotti M, Leonardis D, Bassani G, Frisoli A, Bergamasco M. Evaluating Virtual Embodiment with the ALEx Exoskeleton. In: Malika Auvray, Christian Duriez (Eds) Lecture notes in computer science.;133–40.
58. Thikey H, van Wijck F, Grealy M, Rowe P. A virtual avatar to facilitate gait rehabilitation post-stroke. Gait Posture. 2014;39:S51–2.
59. Ochoa J, Sternad D, Hogan N. Treadmill vs. overground walking: different response to physical interaction. Journal of Neurophysiology. 2017;118(4):2089–102.
60. Stanos S. Focused review of interdisciplinary pain rehabilitation programs for chronic pain management. Curr Pain Headache Rep. 2012;16(2):147–52.
61. Chauvet-Gelinier JC, Bonin B. Stress, anxiety and depression in heart disease patients: A major challenge for cardiac rehabilitation. Ann Phys Rehabil Med. 2017;60(1):6–12.
62. Deterding S, Dixon D, Khaled R, Nacke L. From game design elements to gamefulness: Defining "gamification." Proceedings of the 15th International Academic MindTrek Conference on Envisioning Future Media Environments - MindTrek. 2011; 11:9–15.
63. Kim WS, Cho S, Ku J, Kim Y, Lee K, Hwang HJ, et al. Clinical application of virtual reality for upper limb motor rehabilitation in stroke: Review of technologies and clinical evidence. J Clin Med. 2020;9(10):3369.
64. Qiu Y, He X, Li Z, Peng Z, Huang Y, Yu X. Wearable Sensors for Motion and Electrophysiological Signal Tracking in XR. Korean Journal of Chemical Engineering. 2024;227.
65. Meng W, Liu Q, Zhou Z, Ai Q, Sheng B, Xie S. Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation. Mechatronics. 2015;31:132–45.
66. Ou YK, Wang Y, Chang HC, Chen CC. Design and Development of a Wearable Exoskeleton System for Stroke Rehabilitation. Healthcare. 2020;8(1):18–28.
67. Thieme H, Morkisch N, Mehrholz J, Pohl M, Behrens J, Borgetto B, et al. Mirror therapy for improving motor function after stroke. Cochrane Database Syst Rev. 2018. https://doi.org/10.1002/14651858.CD008449.pub3.
68. Unberath M, Yu K, Barmaki R, Johnson A, Navab N. Augment Yourself: Mixed Reality Self-Augmentation Using Optical See-through Head-mounted Displays and Physical Mirrors. arXivorg. 2020;02884.
69. Nicolas-Alonso LF, Gomez-Gil J. Brain computer interfaces, a review. Sensors. 2012;12(2):1211–79.
70. Ryu Y, Ryu ES. Overview of motion-to-photon latency reduction for mitigating VR sickness. KSII Transact Internet Inform Syst. 2021;15(7):2531–46.
71. Wang Q, Kang B, Kristensson PO. Supporting Physical and Mental Health Rehabilitation at Home with Virtual Reality Headsets and Force Feedback Gloves. 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW). 2021;685–6.
72. Yu X, Lee B, Sedlmair M. Design space of visual feedforward and corrective feedback in XR-based motion guidance systems. arXiv (Cornell University). 2024;723:1–15.
73. Schmalstieg D, Höllerer T. Augmented reality: Principles and practice. IEEE Virtual Reality (VR). 2017;2017:425–6.
74. Ito K, Tada M, Ujike H, Hyodo K. Effects of the weight and balance of head-mounted displays on physical load. Appl Sci. 2021;11(15):6802.
75. Nazari A, Shahidi A, Kaufman KM, Bondi JE, Alabood L, Jaswal VK, et al. Interactive AR applications for nonspeaking autistic people? - A usability study. CHI Conf Human Fact Comput Syst. 2023;2023:1–15.
76. Barnabé Soedji, Jérémy Lacoche, Villain E. Creating AR Applications for the IOT: a New Pipeline. HAL (Le Centre pour la Communication Scientifique Directe). 2020;1–2.
77. Pingxuan R. AR 3D Magic Book. Proceedings of the 2020 International Conference on Computers, Information Processing and Advanced Education. 2020;244–50.
78. Wu Y, Yu L, Xu J, Deng D, Wang J, Xie X, et al. AR-Enhanced Workouts: Exploring Visual Cues for At-Home Workout Videos in AR Environment. 36th Annual ACM Symposium on User Interface Software and Technology. 2023;1–15.
79. Wang Z, Nguyen C, Asente P, Dorsey J. Point Cloud Capture and Editing for AR Environmental Design. The Adjunct Publication of the 35th Annual ACM Symposium on User Interface Software and Technology. 2022;62.
80. Matthias P, Billinghurst M, Zi Siang See. This Land AR: an Australian Music and Sound XR Installation. 17th International Conference on Virtual-Reality Continuum and Its Applications in Industry. 2019;69.
81. Wang Y, Runting Z, Wu H, Xue G. Material Identification System with Sound Simulation Assisted Method in VR/AR Scenarios. Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers. 2021;575–9.
82. Bermejo C, Hui P. A survey on haptic technologies for mobile augmented reality. ACM Comput Surv. 2022;54(9):1–35.
83. Trepkowski C, Marquardt A, David Eibich T, Shikanai Y, Maiero J, Kiyokawa K, et al. Multisensory proximity and transition cues for improving target awareness in narrow field of view augmented reality displays. IEEE Trans Visual Comput Graphics. 2022;28(2):1342–62.
84. Wittchen D, Martinez-Missir V, Mavali S, Sabnis N, Reed CN, Strohmeier P. Designing interactive shoes for tactile augmented reality. Proceed Augmented Humans Int Conf. 2023;2023:1–14.
85. Pérez-Bahena MH, Niño-Suarez PA, Avilés Sánchez OF, Hernández Beleño RD, Pellico-Sánchez OI. Lower Limb Gait Cycle and Foot Plantar Pressure Data Collection for Assistance and Rehabilitation Systems. Smart Innovation, Systems and Technologies. 2022;25–34.
86. Tahir S, Baig MO, Rathore FA, Aslam H. The emerging role of focal muscle vibration in rehabilitation of neurological disorders. JPMA The J Pakistan Med Association. 2022;72(10):2126–8.
87. Dawson-Elli AR, Adamczyk PG. Design and validation of a lower-limb haptic rehabilitation robot. IEEE Trans Neural Syst Rehabil Eng. 2020;28(7):1584–94.
88. Chen G, Chan CK, Guo Z, Yu H. A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy. Crit Rev Biomed Eng. 2013;41(4–5):343–63.
89. Frölke R, Butz B, Lux G, Gerken J. HoloBoard: Visual augmentation and gamification of balance exercises. Mensch und Comput. 2023;2023:503–7.
90. Ying W, Aimin W. Augmented reality based upper limb rehabilitation system. 13th IEEE International Conference on Electronic Measurement amp; Instruments (ICEMI). 2017;426–30.
91. Sun Y, Tang Y, Zheng J, Dong D, Chen X, Bai L. From sensing to control of lower limb exoskeleton: a systematic review. Annu Rev Control. 2022;53:83–96.
92. de Assis GA, Corrêa AGD, Martins MBR, Pedrozo WG, de Lopes R, D. An augmented reality system for upper-limb post-stroke motor rehabilitation: a feasibility study. Disability Rehabilitation: Assistive Technol. 2014. https://doi.org/10.3109/17483107.2014.979330.
93. Iqbal J, Sidhu MS. Augmented Reality-Based Dance Training System: A Study of Its Acceptance. Lecture notes in computer science. 2021;219–28.
94. Burke JW, McNeill MDJ, Charles DK, Morrow PJ, Crosbie JH, McDonough SM. Augmented Reality Games for Upper-Limb Stroke Rehabilitation.

Second International Conference on Games and Virtual Worlds for Serious Applications. 2010;75–8.
95. Vidrios-Serrano C, Bonilla I, Vigueras-Gomez F, Mendoza M. Development of a haptic interface for motor rehabilitation therapy using augmented reality. 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 2015;1156–9.

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