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# Gamified virtual reality in post-stroke neurorehabilitation: a systematic review

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**Introduction:** Huge and increasing global rehabilitation needs, affecting more than 2.4 billion people, require the mainstream adoption of the latest innovative technological solutions, including but not limited to virtual reality (VR), robotics, artificial intelligence (AI), or games. This systematic review focuses on the use and potential of gamified VR in post-stroke neurorehabilitation to effectively address patient engagement and motivation, scalability, costs, and the scarcity of specialists.
**Methods:** Our review, conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, identified 4,856 records narrowed down to 66 key studies from five major databases. These studies were categorized and analyzed based on the technologies used, game mechanics, gamification techniques, adaptation to the user, and evaluation procedure.
**Results:** Our findings draw significant conclusions for each of these aspects and ultimately highlight the potential of gamified VR to become a mainstream neurorehabilitation technology for post-stroke patients, scalable to societal needs and improving recovery outcomes. Our review concludes with a discussion of the future directions and implications for clinical practice in neurorehabilitation using gamified VR technologies.

KEYWORDS
exergame, gamification, neuro-motor rehabilitation, stroke, virtual reality

## 1 Introduction

Recent statistics (2022) by the World Health Organization show that 2.4 billion people worldwide require some form of rehabilitation. For example, 394 million people across Europe, nearly half of the population, need rehabilitation. It is estimated that there are more than 49 million disability-adjusted life years (DALY) caused by a medical condition requiring rehabilitation (World Health Organization, 2022). Contrary to popular belief, the category with the highest number of people needing rehabilitation is not elderly people: the 15–64 age category represents more than 64% of people affected by these disorders. The prevalence of the need for rehabilitation is largely due to musculoskeletal and neurological disorders (73%), with more than 287 million people across Europe affected (Mishra et al., 2023).

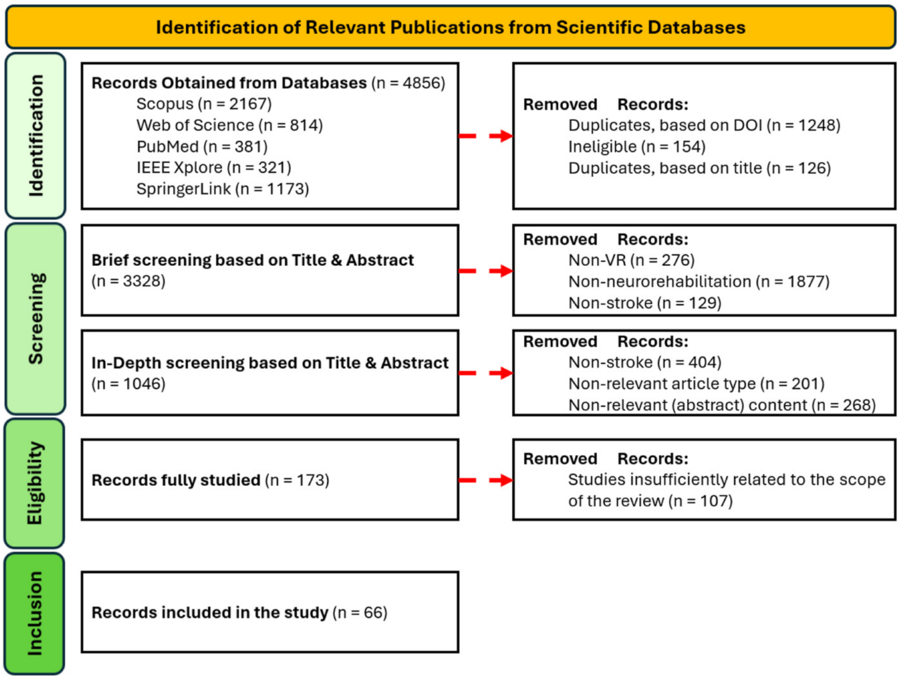

FIGURE 1
PRISMA statement model adapted and applied in this study.

The only solution for improving lost functions and disabilities is through neurorehabilitation, an extensive, sometimes repetitive process, which includes various specific procedures guided by physicians. Unfortunately, people often do not benefit from neurorehabilitation for various reasons, including the low number of specialists (statistics showing 12 times fewer physiotherapists than needed across Europe (World Health Organization, 2022), high costs, lack of accessibility, or lack of motivation.

One possible solution to all the above issues is the use of virtual reality (VR). This emergent technology allows the creation of realistic virtual environments in which personalized rehabilitation exercises can be performed (Moldoveanu et al., 2019; Stanica et al., 2020). Through telemedicine, therapists can monitor their patients' progress in VR from a distance and personalize their training schedule and intensity. Virtual reality devices are becoming more accessible with the advancement of technology, while complex systems combining VR and robotics can speed up recovery through augmented feedback (Caraiman et al., 2015; Ferche et al., 2015). Virtual reality can make the neurorehabilitation process more engaging, and even fun, through gamification. It is essential to find new ways of solving the motivation issue, as even the most efficient rehabilitation plan will have no effect if the patient does not follow through.

Our current article presents the status of neurorehabilitation research involving gamified virtual reality. While many review studies that analyze the use of VR for neurorehabilitation, few surveys also focus on the gamification component. Even though some reviews touch both the subject of VR and that of gamification in the context of rehabilitation (Tosto-Mancuso et al., 2022; Adlakha et al., 2020; Mubin et al., 2019; Tuah et al., 2021), none go in depth regarding existing evaluation metrics that demonstrate the effectiveness of these solutions. In this context, our article tries not only to identify existing VR technologies and gamification strategies, but also to point out potential gaps in evaluation procedures, with the purpose of designing efficient, validated solutions for neurorehabilitation. We conducted a systematic analysis of articles focused on gamifying neurorehabilitation through virtual reality. Section 2 presents our thorough review methodology of the relevant research articles using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline, while Section 3 summarizes the most relevant information extracted based on the main technology used. Section 4 discusses the main gamification aspects identified in the selected articles. Section 5 presents aspects related to adaptability in rehabilitation solutions: calibration to the user's range of motion, difficulty adjustment, and user preferences. In Section 6, we describe existing evaluation methodologies, giving a perspective on how new rehabilitation solutions should be piloted and assessed. Finally, Section 7 concludes the subject.

## 2 Review methodology

This process involved an extensive literature review, a rigorous stage of article collection, a presentation of the results obtained and their interpretation, and drawing several conclusions.

The applied methodology was based on the identification of the most relevant publications in the specified field, using the PRISMA Statement model, which we adapted, as summarized in Figure 1 and explained step by step below.

TABLE 1 Number of publications identified in each scientific database and their total.

| Scopus | Web of science | PubMed | IEEE xplore | Springer nature link | Total |
|---|---|---|---|---|---|
| 2,167 | 814 | 381 | 321 | 1,173 | 4,856 |

## 2.1 Identification stage

For the first phase, the identification stage, we collected articles from five renowned international scientific databases: Scopus (Elsevier), Web of Science, PubMed, IEEE Xplore, and Springer Nature Link. The search was performed on the information available in the title, keywords, and abstract, using the advanced search function available on each of these platforms. For example, the following formula was used in the advanced search in Scopus:

TITLE-ABS-KEY ((“stroke” OR “post-stroke” OR “post stroke” OR “rehabilitation” OR “neurorehabilitation” OR “neurological rehabilitation” OR “neuromotor rehabilitation” OR “neurological disorder” OR “neurocognitive disorder” OR “neuromotor”) AND (“virtual reality” AND “game”)).

For the other databases, the formula was adapted to match the required language, but the search criteria were faithfully preserved. We did not use temporal filters: the publication date was influenced only by the search date in the databases. Therefore, the retrieved articles spanned from 1992 until January 2025. We did not impose linguistic filters. However, due to the keywords used in the search stage, most retrieved articles were in English (with a small number of articles in Spanish and French, which were filtered out in the screening phase). Regarding the type of publication, where possible (Scopus, WoS, and Springer Nature Link), we filtered out articles that did not present original research (selecting Article, Conference paper, Proceedings paper, Research article types). PubMed exposed many filters we did not use, to avoid excluding relevant articles that could have been imperfectly indexed. The search on the IEEE Xplore database retrieved only documents in the conferences, journals, early access, and magazines categories, so we decided not to use any filtering for the document type. Regarding domain filtering, we did not impose any limits to ensure that we do not miss out on relevant articles. Both the number of publications identified in each of these databases and the resulting total number are shown in Table 1.

To ensure the best conditions for the analysis, we exported the lists with the results obtained from the searches on each platform, in either MS Excel XLS or CSV format. Due to differences between the exports in terms of the contained columns, the next step was to unify them into a single MS Excel file. In this new table, we included the columns with information related to “Title,” “Authors,” “Year of Publication,” “Publication,” “Digital Object Identifier (DOI),” and “Abstract,” considering that they represent the necessary information for continuing the analysis under optimal conditions.

To prepare for the examination stage, we started by removing records with the same DOI. As a result, 1,248 publications were excluded from an initial list of 4,856 articles. Then, we noticed that there were some ineligible entries in the table (e.g., entries that only contained the name of a proceeding and general data about it, without referring to any article *per se*). To identify them all, we searched for “Proceeding,” “Editorial,” and “[” in the title column and removed those articles manually (154 entries were removed). Finally, we removed 126 duplicates based on the title. At the end of this stage, 3,328 publications remained.

## 2.2 Screening stage

The screening stage was divided into two phases: a brief screening, based only on automatic searches in the title and abstract or on manually inspecting the titles (without manually analyzing the abstracts), and an in-depth screening, in which all the titles and abstracts were manually studied.

### 2.2.1 Brief screening

In total, 3,328 records proceeded to the examination stage. First, we removed all publications that did not refer to virtual reality (VR). We searched the title column for various keywords (“augmented”/“machine”/“artificial”/“robot”), and if the abstract did not mention virtual reality at all, we eliminated them. At this step, 276 entries were excluded.

This was followed by an intensive manual review of the titles for the remaining 3,052 publications to ensure that all records that did not refer to neurorehabilitation were removed. This step eliminated the largest number of articles, specifically 1,877.

Next, analyzing only the title, we searched for some common conditions requiring motor rehabilitation (“palsy”/“Parkinson”/“sclerosis”) other than stroke and broadly eliminated another 129 entries from the table.

At the end of this brief screening stage, 1,046 publications remained.

### 2.2.2 In-depth screening

We then manually checked the remaining titles and abstracts in detail to exclude those that did not refer to stroke, and 404 articles were removed.

In the identification stage, we could not use the filters on all the databases to include only original research articles. Therefore, from the remaining 642 records, we eliminated 201 publications based on the abstract, identifying article types that were not of interest to this study (e.g., reviews, meta-analyses, and protocols from medical institutions).

For the remaining 441, we carefully reviewed the abstract to ensure that only the most relevant studies for the next stage remained. For example, we removed all entries that did not emphasize gamification, keeping only the most current, relevant, and valuable articles for our goal. After a long process, we managed to reduce the list to 173 by eliminating 268 entries.

## 2.3 Eligibility stage

In the eligibility stage, we fully analyzed the content of the 173 scientific articles identified above.

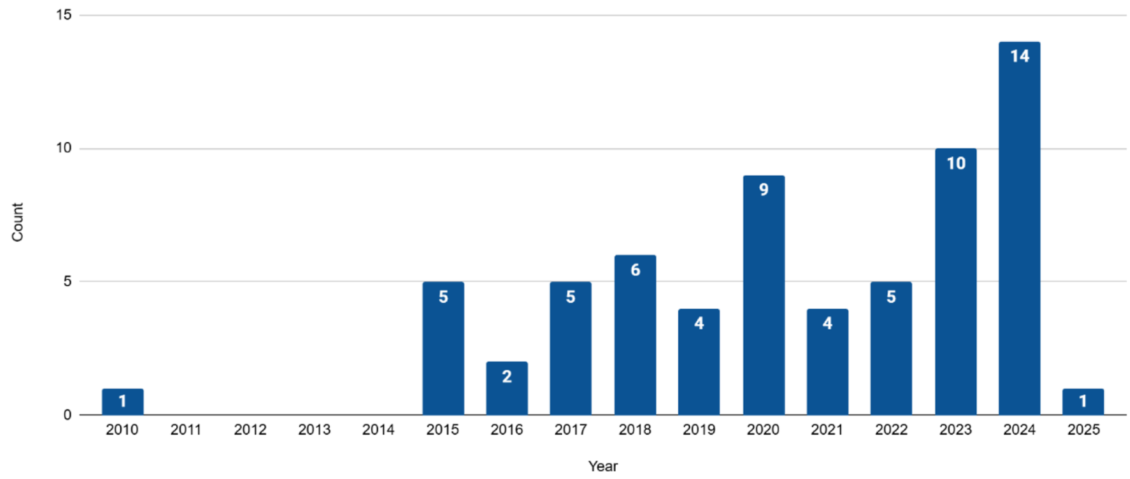

FIGURE 2
Histogram of publication years for the included articles.

Regarding a risk of bias assessment, we did not use a known bias scale to grade the remaining articles, but in the inclusion stage, we decided to remove 107 of 173 studies after a full-text analysis. The removal was accomplished based on the relevance of those articles in relation to the subjects that we approached in this study: technologies, gamification strategies, adaptation to user, and evaluation metrics. Even if this filtering step is subjective, the large number of articles that were included in the study minimizes the risk of missing out on relevant information about the subject.

## 2.4 Inclusion stage

Figure 2 presents the distribution of publication years for the 66 included articles.

## 2.5 Analysis objectives

The detailed analysis of the selected 66 scientific articles included four main directions, each with subsequent objectives. The first direction was to identify popular technologies used in ICT-based neurorehabilitation, which were divided into commercially available systems (VR headsets and optical tracking systems), custom solutions, and robotics-enhanced systems. The next direction was to analyze gamification strategies and types of games appropriate for VR-based rehabilitation. Next, we identified approaches related to the adaptation of the environment/tasks/user interface to the needs of the patients. The last direction, focused on clinical trials and studies with patients, aimed to assess the effectiveness and acceptance of VR-enabled neurorehabilitation systems.

# 3 Technologies used

Virtual reality is a broad term that refers to an environment simulated by computer technology. This environment can be displayed on immersive devices, such as head-mounted displays (HMDs) and cave automatic virtual environments (CAVEs)—rooms where virtual imagery is projected onto multiple walls or curved screens, or can use non-immersive displays, such as monitors, smartphones, tablets, or interactive whiteboards. During our analysis of the selected articles, we identified popular technologies used in VR-based neurorehabilitation. While many solutions use immersive VR headsets, such as Oculus or HTC Vive, other systems are based on non-immersive displays and optical tracking technology (e.g., Kinect and Wii). For a more personalized rehabilitation experience, researchers often combine immersive or non-immersive displays with custom technology, used either for tracking the hands and fingers or as input controllers. A recent trend in rehabilitation combines the advantages of both virtual reality and robotics. While very efficient, the high cost of robotic systems comes with affordability issues. In this chapter, we divided the identified VR-based neurorehabilitation technologies into commercially available systems (VR headsets, non-immersive displays, and optical tracking systems), custom neurorehabilitation solutions, and robotics-enhanced systems.

## 3.1 Commercially available tracking systems

Many of the selected articles utilize commercially available systems for creating a neurorehabilitation tool. This allows for better availability and reliability of the hardware but sometimes incurs high costs.

### 3.1.1 VR headsets

Virtual reality allows the creation of a wide range of realistic environments. It includes the use of various devices that can ensure movement detection, as well as provide visual, audio, or even haptic feedback. Early VR-based systems frequently used a mix of an Oculus Rift Development Kit 2 and a Leap Motion device to ensure three degrees of freedom and hand tracking (Dias et al., 2019). Since then, VR systems have been constantly evolving, from high-end systems requiring a powerful computer to standalone, wireless devices, such as Meta Quest devices (Paraense et al., 2022) that do not require a PC connection or external sensors. The latter comes with a drop in tracking accuracy and sometimes resolution, yet they have lower prices and are easier to use.

Salisbury et al. (2020) proposed CognviveVR, a telerehabilitation system for the upper limb that uses VR technologies. The system includes a patient module (with a variety of mini-games that can be performed independently with increased levels of difficulty, such as a tennis-like game where the user must direct a ball to hit some blocks), a reporting system to collect relevant exercise data, and a clinician dashboard, for supervising the patient's results and progress. CognviveVR is a relatively recent study, and its development is iterative, thus, the system has allowed technological upgrades, from an Oculus Rift system (headset, trackers, and controllers) to a standalone, wireless HTC Vive Focus Plus system, based on an inside-out tracking technology. By not requiring external sensors, the at-home, self-administered VR treatment becomes easier to use and is less prone to tracking errors caused by sensors' misplacement. HTC Vive is also the technological choice of Christou et al. (2018a) and Christou et al. (2018b), thanks to its high precision in terms of movement detection. The 2 mm maximum error of position detection of the HTC Vive VR system allows the implementation of the Buzzwire game, an exercise aimed at training fine motor control skills of fingers and hands, which consists of a wire shaped in different curves and a circle placed around it that must be moved by the user. In addition to the head-mounted device, external sensors, and hand controllers, the system allows the use of a Vive tracker, a wireless accessory connected to a rod, with high accuracy and no perceptible lag, which enables the natural control of the circle along the wire in the Buzzwire game implementation. Vive trackers are used in other systems as well (Homola et al., 2022), facilitating the use of leg muscles in a VR game for collecting virtual stars or together with a treadmill (Bovim et al., 2021) in the VR Walk game to evaluate balance and lower-limb functionalities.

The reports about the systems presented so far focus mainly on functionalities and do not mention the costs of the system for a regular user who would want to train at home. In addition to the cost of the VR hardware, most advanced VR equipment requires a high-end computer, which can be quite costly. Rojo et al. (2022) propose a solution to this issue by creating a remote virtual reality system for upper-limb treatment. Their VR application runs on a high-end cloud server, the video signal is downsampled and encoded, then sent to a less powerful computer (owned by the patient), to which the headset and controllers are connected. All data from the VR sensors (position, rotation, and interactions) are sent from the client to the server to be processed and then locally rendered to the user on a VR headset such as Oculus Rift or HTC Vive. The system uses only the end-effectors (controllers) and applies inverse kinematics to calculate inner joints' angles and evaluate the upper limb's range of motion in the various activities that the patient must perform.

Some scientific articles have analyzed the effectiveness of low-cost smartphone VR in treating neurological disorders. Quarles (2015) uses a headset based on a waterproof smartphone and a second smartphone strapped to the user's chest for vibration feedback. The system provides three degrees of freedom body orientation tracking and punch detection. This investigation employs a game requiring the user to punch a shark underwater and concludes that different balance and mobility issues are easier to handle underwater. The research must, however, be validated with a significant number of patients with stroke, as it was tested with only one person who had multiple sclerosis. Other low-cost VR systems (Zirbel et al., 2018) combine smartphone-based virtual reality and electromyography (EMG) using the Myo gesture control armband. This device is attached to the user's forearm and can identify its position, rotation, predefined gestures of the fist, and muscular activity through EMG sensors. Another system that combines smartphone-based virtual reality and EMG, presented by Kamatchi et al. (2023), employs four types of games (shooter, object slicer, ping pong, and snow strike) to improve the upper-limb function in stroke patients.

### 3.1.2 Non-immersive displays and optical tracking systems

Kinect-based systems have shown considerable popularity over the years in neurorehabilitation research—a fact reflected also in our current article, as more than half of the VR-centered selected studies focus on Microsoft Kinect. Allegue et al. (2021) present a telerehabilitation system ensuring home-based exercises for chronic stroke patients, using Kinect, a video camera, and a PC. These devices ensure the monitoring of the rehabilitation process in real time by a clinician through videoconferencing with ReactJS. The results might, however, depend on the person's technical and emotional preparedness to manage various situations (e.g., technical issues), as the number of devices and software applications that must be used at the same time is quite large. Another research using Kinect focuses on its technical assessment rather than clinical analysis. Benrachou et al. (2020) utilize a low-cost system based on Kinect and focus on the virtual avatar to reduce the discrepancies between real-life movement and in-game animations. The avatar's animations are thus viewed as an extension of the patient's body, and the article reports that anthropomorphic avatars are preferred over skeletal models.

The popularity of Kinect can be justified as it is a device that provides full-body tracking out of the box, and custom neurorehabilitation games can be easily created using a standard game engine. Unfortunately, the product has been discontinued since 2017, while its successor, Microsoft Azure, is available only for development. As shown by Trombetta et al. (2017), immersion plays an essential part in increasing the trainees' motivation, so the researchers decided to use Kinect for full-body tracking in connection with an Oculus HMD as a display. Their 2017 approach can now be regarded as deprecated, as a complete VR system, such as Oculus or HTC Vive with extra sensors, can ensure both tracking and visual display; however, the latter is a more expensive and difficult to configure alternative than Kinect.

Another great advantage brought by Kinect is the possibility of measuring trajectory, range of motion, joint velocity, acceleration, reaching time, and joint torque for the moving joints (Dubey and Manna, 2019). A basketball game was developed as a proof of concept, and the system generates a report with measured parameters that can be interpreted by a physiotherapist using MATLAB.

Interestingly, Kinect can be successfully used for creating a multi-user system, in which multiple clients (to a maximum of four) using Kinect can connect simultaneously to a hospital's central server (Tsoupikova et al., 2016).

Some systems using Kinect have exceeded the research level and reached commercialization. MIRA Rehab (Repanovici et al., 2020) was validated in 2015–2016 in several countries. It is a complex system including local games and web games, recording data and statistics for performance, offering real-time feedback, and making patient progress available to the doctor through telemedicine. To date, it has been used in more than 70,000 rehabilitation sessions, especially in the United Kingdom.

Various optical and inertial measurement unit (IMU)-based devices, such as Microsoft Kinect, Leap Motion, and the Myo gesture control armband, have been combined to create complex rehabilitation systems (Holmes et al., 2015). They rely on the use of a smooth user interface, allowing natural movements of the patients and creating with the system a rehabilitation game model that can become a standard for the improvement and increased efficiency of future rehabilitation games.

Studies using other optical-based tracking technology (e.g., Wii device) are often incorrectly presented as virtual reality, even though the degree of immersion is nonexistent. One such study (Lee et al., 2018) presents a system consisting of a Wii balance board, a simple canoe, grip gloves, a safety belt, and a TV screen. They use a commercially available Wii canoe paddling game and demonstrate its efficiency as a rehabilitation procedure for subacute stroke. Drawbacks include the requirement of many hardware components, the high costs, and the deprecation of the Wii device.

## 3.2 Custom VR rehabilitation systems

Often, researchers implement their own hardware, usually based on an inertial measurement unit. Such an approach is demonstrated by Goršič et al. (2017), in which the device, a Bimeo arm, which is based on three IMUs and a Logitech joystick, is used for creating a competition-based upper-limb rehabilitation system, which proves to be both effective and low-cost. Avola et al. (2019) describe their own hardware consisting of a custom infrared stereo camera attached to a head-mounted display (for hand and finger tracking), a time-of-flight depth camera (for skeleton data), and a series of custom games focused on balance training. Such a system has the advantage of being low-cost but may experience latency problems for the patients, which can impair the exercises. On the positive side, therapists have shown interest in the gamification part, especially the scoring system, considering it useful for real-time monitoring of the patients. The users showed interest in the experience itself, as it can bring a significant gradual recovery of their skills.

Another study (Lin et al., 2017) based on custom-made components analyses the effects of a VR-based rehabilitation procedure for post-stroke patients using a brain–computer interface. They use an Arduino-based motion-tracking device (MTD), a laptop, and an EEG device together with a custom Unity-based cannon shooting game (movements performed by the patient are used to load the cannon and then direct it to hit a ship). This creates a low-cost, wireless alternative, but the MTD requires a 1-min initial calibration each time it is used. A different Arduino-based system (Alexandre et al., 2019) combines a VR headset and smart gloves equipped with various sensors to measure rotation, acceleration, and force, creating a complex yet affordable system.

Another custom system called SilverTune (Luo et al., 2021) is made from a Bluetooth module, an accelerometer, and a gyroscope, with the goal of simulating multiple senses during rehabilitation procedures. Two games, horse racing and table tennis, can be controlled using SilverTune, which is also capable of offering haptic or audio (various instrumental sounds) feedback for increasing the user's enjoyment of the training.

A custom tracking system that uses myoelectric pattern recognition (MPR) and surface electromyography (sEMG) was proposed by Munoz-Novoa et al. (2024). The system is used to detect hand and upper-limb movements of the patient. The MPR algorithm decodes sEMG signals from the arm, with the output used to control a virtual arm displayed on a computer screen.

Proprietary systems, such as Magic Glass (Stephenson et al., 2020), aim to break the boundaries between research and commercialization, focusing on user-centered design and developing their own system based on mirror therapy. In 2020, they published a complex and complete study protocol suitable for acute, subacute, and chronic stroke patients, including criteria for selecting the study population, questionnaires, outcomes collected, scales used for monitoring, statistical analysis, and ethical considerations. Unfortunately, no updates have been provided since, and the dedicated website of the product is no longer available.

Liu et al. (2024) utilize the Virtual Reality Digital Twin Stroke Hemiplegia Rehabilitation and Training System (Beijing NuoYiteng Technology Co., Ltd.). This system integrates a head-mounted VR-integrated device, motion capture gloves, a high-precision binocular camera, and a display screen. The VR headset and gloves allow patients to interact with the virtual environments and facilitate spatial tracking. Patient movements and positions are recorded in real time using a combination of inertial sensors and optical tracking technology.

Tan et al. (2024) use a custom-developed NEAR3 Force Plate as an input controller for two non-immersive VR rehabilitation games designed for trunk rehabilitation in a stable sitting position. With this device, they also measure ground reaction forces and the center of pressure (CoP) during various rehabilitation activities.

## 3.3 Robotics-enhanced tracking systems

Recent research combines the advantages of both robotics and virtual reality for creating rehabilitation systems. Huang et al. (2017) present an example that uses an Amadeo robotic glove to help stroke patients recover or improve their affected fine motor skills. The virtual scenes can be visualized in two different modes: non-immersive, on a computer screen, or immersive, on an Oculus Rift VR headset. The robotic hand device, combined with a neural network, can assist the training process by providing force assistance or trajectory guidance.

Another example is presented by Gao et al. (2023), who describe a system composed of four modules: an EEG signal collection and analysis module, a control center, a VR module, and a hand soft rehabilitation module. EEG signals are collected and processed, then sent by the control center to both the VR module and the hand soft rehabilitation exoskeleton. The hand exoskeleton receives information about the rehabilitation exercises and controls the patient's hand to move accordingly. The exoskeleton is also responsible for detecting the real-time motion state of the hand.

Larger robotics, such as the Armeo Power upper-limb exoskeleton, can be successfully used with gamification elements in virtual reality scenes. Stockley and Christian (2022) introduce a novel neuroanimation therapy for stroke patients, concentrating on the use of robotic devices as a helping tool for performing a large number of correct movements in the virtual scene to accomplish the tasks in the game. The disadvantages of such a system include high costs and the fact that the system must always function correctly, as it could otherwise become frustrating for both doctors and their patients. Another cumbersome robotics-based configuration is studied by House et al. (2015) and House et al. (2016). They use the Bright Arm Duo system (robotic table, sensorized forearm support, and a PC running a series of virtual mini-games). Even though they observed improved strength in the shoulder, grasp, active range of motion, and supported arm reach, the hardware is bulky, with clear limitations (e.g., it does not allow for extending the fingers or rotating the arms).

Interesting and lower-cost robotics, such as Lego-based exoskeletons, are used together with HTC Vive Pro and Vive trackers (Homola et al., 2022) for game-based rehabilitation, but their results show that a different material for the exoskeleton would be more reliable and provide better outcomes. The RAPAEL Smart Glove is another accessible robotic device used in research together with transcranial direct current stimulation (Lee and Cha, 2022), being integrated into non-immersive virtual scenes.

Lower-limb rehabilitation requires high costs and large robotic devices, such as those described by Feng et al. (2020). A robot with six articulations for each joint, a control and sensor system, as well as a chair for sitting, is used for patients with acute stroke. The system can only be used in the presence of a doctor who will configure it according to each patient's needs and condition. The robot is controlled by the patient to execute the tasks in a VR-space shooting game with various levels of difficulty.

## 4 Games and gamification

Early studies show the potential of social media and games in the rehabilitation process (Tatla et al., 2015) underlying the therapists' opinion. They highlight the usefulness of games for the neurorehabilitation process of the upper limb, as they can offer real-time feedback, improve socialization, and provide intrinsic motivation.

Many of our selected articles heavily rely on games and gamification techniques. Thus, one of the main goals of our current analysis is to evaluate the potential of games and gamification principles in neurorehabilitation. Table 2 in Annex 1 contains the most relevant gamification elements found in the identified games. Table 3 in Annex 1 summarizes the identified games and their most prominent gamification elements, as well as the articles in which they are described, as some of the games are presented in more than one scientific article.

In this section, we illustrate how relevant articles address various aspects related to gamification and related aspects such as competition, collaboration, etc.

Gamification has been widely used in many studies describing neurological rehabilitation (Charles et al., 2020). Zuki et al. (2024) show the significance of gamification elements and enriched environments in VR rehabilitation games. The study presents two variants of a pick-and-place game, in which participants are required to move objects from one location to another. One variant has minimal content and limited gamification elements, while the enriched variant incorporates rich visuals, gamification elements, and *progression* elements. The findings show that the enriched variant had a significant positive impact on participant motivation.

Borrowing mechanics from commercial games and adapting them for rehabilitation purposes can represent a simple yet efficient strategy. Such an example is given by Holmes et al. (2015), who introduced a rehabilitation game model (RGM) that can assess the usefulness of certain neurorehabilitation exercises based on the user's profile. Games from different genres are used, including action, adventure, role-playing, simulation, and strategy, and established rehabilitation games are included in the study as well. Different gamification techniques are used, such as *scoring* systems, achievements, and *powerups* (Easter eggs). Their results after the evaluation process show that existing games emphasize achievements, while people requiring rehabilitation after a stroke would appreciate more aspects related to socializing and creativity. Commercial games can also be used as a reference compared to custom-developed VR rehabilitation games, as described by Chen et al. (2023).

Daily activities and real-life scenarios are often reproduced in virtual reality systems for neurorehabilitation. A significant advantage of games that reproduce daily activities and real-life scenarios is their accessibility: they require no prior experience in gaming or virtual reality for the patients, thus enhancing the rehabilitation experience (Chen et al., 2025). Rojo et al. (2022) propose six daily activities (hand washing, drink pouring, playing piano, petting animals, picking fruit from trees, and picking vegetables from the ground). These activities have the goal of helping people recover their upper-limb functionality in a gamified manner. The activities are thus presented as a series of *tasks* that must be performed correctly to ensure progress. Each action required in a simulated activity is thoroughly described in terms of which joint/movement is used (e.g., shoulder flexion). The use of bimanual interaction should be investigated to determine if it is better than using one arm at a time (with the focus on the side needing rehabilitation). The study of the usability and feasibility of the application emphasizes that the experts' opinions are more important in this matter than the users' feedback, as the physiotherapists can better understand how to create a successful VR rehabilitation program. Their research offers many valuable takeaways and shows that immersive VR is more efficient than non-immersive rehabilitation (e.g., Kinect), therefore, headsets are preferred even if they are challenging for some people with stroke or cerebral palsy. However, Trombetta et al. (2017), although stating that HMD-based VR training is more efficient in terms of motivation and immersion, suggest that patients are more comfortable and able to perform tasks in the third person (using Kinect and a TV monitor). Other research presenting gamified routine activities (Dias et al., 2019) includes VR activities such as a lift game (barbell lifting), apple eater, or dishwasher. Gamification elements include score and constant positive *feedback*. One issue identified by the users in these games is related to the lack of naturalness of some tasks, especially in the apple-eating game, where the virtual apple

TABLE 2 **Common gamification elements present in VR stroke rehabilitation games and their descriptions.**

| Gamification element | Description |
|---|---|
| Score | A score is a numeric value that increases when a player successfully completes actions or tasks required by the game. It can be used as a measure of player performance and can increase motivation by encouraging the players to improve upon their previous results |
| High score | The maximum score that the patient obtained within a game |
| Time | Time can be used as a gamification element by measuring the speed of completing the actions or tasks required by the game, serving as an indicator of performance or progress. Time can also be used to limit the duration of the gameplay sessions, aligning them with the conventional therapy protocols. Additionally, tracking the total time participants engage with the game can offer insights into their level of motivation and willingness to play the rehabilitation games |
| Performance | Performance refers to the evaluation of how effectively a player executes the actions required within the game. This assessment can be based on various gameplay-related metrics such as scores, completion times, or the precision of the movements. Measuring performance helps quantify a player's functional ability and progress |
| Levels of difficulty | Depending on the functional abilities of the patients, the exercises they need to execute during rehabilitation might differ in difficulty. For this reason, many rehabilitation games have predefined levels of difficulty or provide a way for therapists to change the parameters of the games to suit the needs of the patients |
| Tasks | The games require the players to do certain things within the virtual worlds to achieve the intended goals |
| Feedback | Feedback is the information provided to the players about their actions and performance. Feedback can take multiple forms. One main form of feedback is the real-time representation of player movements within the virtual environment. Another form of feedback consists of visual or auditory cues triggered when the player interacts with the virtual environment or the game elements |
| Progression | Progression refers to the tracking of the player's performance over time within the game. Based on these performance data, the game may change the tasks or adjust the difficulty levels. Visible progression can also be used as a motivational factor by providing a sense of achievement in the therapeutic process |
| Dynamic difficulty adjustment | The difficulty of the game may change automatically during gameplay depending on the player's performance or affective state |
| Self-paced design | Self-paced design refers to gameplay that allows the players to complete the tasks at their own pace, without enforcing time limits or pressure from game-related constraints |
| Multiplayer | The games can be played by multiple participants within the same virtual environment, allowing for either cooperative or competitive interactions. In the context of rehabilitation games, players may all be individuals undergoing therapy, or a mix of patients and healthy participants |
| Powerups | Powerups are interactive objects found within the virtual environment that can be collected by the player to temporarily enhance their in-game abilities |
| Obstacles/enemies | Obstacles or enemies are virtual objects that players must avoid. In most cases, avoiding them implies not touching them using the virtual representation of the limbs used in the games. In other cases, the obstacles/enemies must be destroyed, either through specific movements or game mechanics such as shooting |
| Countdowns | Countdowns are short time intervals displayed before the start or resumption of the gameplay. They give players a brief moment to prepare and adapt to the environment |
| Encouragement | Encouragement refers to the use of positive feedback when players successfully complete game-specific tasks. This reinforcement helps motivate players to continue playing and improve their performance |
| Character selection | Character selection allows participants to choose their virtual avatar within the game environment. This can strengthen the sense of presence, potentially increasing engagement during rehabilitation |

sitting in the person's mouth does not have a realistic position. Game designers should also avoid the creation of games in which smell or taste senses would contribute significantly to immersion, as these senses cannot be stimulated properly in virtual reality.

Other researchers use a suite of mini-games based on routine tasks that must be completed. Examples are given by Chen et al. (2023) and Chen et al. (2025), in which a set of five games designed for upper-limb rehabilitation is presented: Dumbbell-lifting, Fishing, Sheep-whacking, Apple-picking, and Balloon-popping. These games target specific exercises for the shoulder, elbow, forearm, wrist, and reaching movements. Allegue et al. (2021) introduced another set of five upper-limb rehabilitation games: Space race, Fish frenzy, Pop clap, Catch and carry an apple, and Kitchen clean up. The games include tasks such as reaching/moving targets, picking up objects, and gaming principles like score, *time*, warning for failure, and auditory feedback. Difficulty adjustments are also possible in this application, but they are not applied automatically. The therapist can control the number of rounds, repetitions, time, speed, precision, and shape of objects. House et al. (2016) present a different suite of virtual mini-games: Breakout 3D (two paddles bouncing a virtual ball toward an array of crates), Card island (card matching memory game), Pick and place (moving balls game), Musical drums (hitting notes to play drums), and Kites (fly kites through moving rings of different colors). Gamification elements include avatars and *multiplayer* mode.

Another system that emphasizes the importance of gamification elements in stroke rehabilitation is presented by Rubino et al. (2024). Their system incorporates a game in which patients control an on-screen spaceship by moving their hand to intercept moving asteroids. The game includes auditory cues, visual feedback, and

TABLE 3 Game summary including types of games, game mechanics, and their corresponding articles.

| Game name | Element | Article |
|---|---|---|
| Dumbbell-lifting, Fishing, Sheep-whacking, and Balloon-popping | Tasks, feedback, progression, and levels of difficulty | Chen et al. (2023); Chen et al. (2025) |
| Free movement control<br>Movement matching | Performance, levels of difficulty, tasks, and feedback | Munoz-Novoa et al. (2024) |
| Bowling, Fruit collection, Arcade, Hammer, and Attic | Score, time, performance, levels of difficulty, tasks, feedback, and progression | Masmoudi et al. (2023) |
| Pick and place | Score, time, performance, levels of difficulty, feedback, progression, dynamic difficulty adjustment, countdowns, and encouragement | Zuki et al. (2024) |
| Hand grab exercises and Hand movement exercises | Score, performance, levels of difficulty, tasks, feedback, progression, countdowns, and encouragement, hints | Bedendo et al. (2023) |
| Pick and place, Grab and throw, and Tennis | Score, performance, tasks, feedback, progression, and encouragement | Kowsalya et al. (2024) |
| Carpenter, Tejo, and Farmer | Score, performance, levels of difficulty, tasks, feedback, progression, dynamic difficulty adjustment, countdowns, and encouragement | Castillo et al. (2024a); Castillo et al. (2024b) |
| Fruit catching, Tennis, Obstacle avoidance | Performance, levels of difficulty, tasks, feedback, and progression | Liu et al. (2024) |
| Skicross, Bounty Super G | Performance, levels of difficulty, tasks, feedback, progression, and encouragement | Korkusuz et al. (2024) |
| Box and block test | Score, time, performance, tasks, and feedback | Everard et al. (2024) |
| Intercept asteroids | Score, performance, levels of difficulty, tasks, feedback, progression, dynamic difficulty adjustment, and encouragement | Rubino et al. (2024) |
| Whack-a-mole, Tilt the maze | Score, performance, levels of difficulty, tasks, feedback, progression, dynamic difficulty adjustment, self-paced design, and encouragement | Tan et al. (2024) |
| Reach game, Sequence game, Flip game, Opening/closing game | Performance, levels of difficulty, tasks, feedback progression, and encouragement | Aguilera-Rubio et al. (2024) |
| Virtual study environment, Billiards, Tree chopping, Exploration | Performance, levels of difficulty, tasks, feedback, progression, and encouragement | Gao et al. (2023) |
| Gesture-controlled rhythm game | Score, performance, levels of difficulty, tasks, progression, and feedback | Bae and Park (2023) |
| Balloon popper, Bubbles, Firefighter, Animal hurdler, Fruit catcher, Hay collect, Scarecrow, Pump the wheel, Horse runner, and Butterfly catcher | Score, levels of difficulty, tasks, feedback, progression, obstacles/enemies, countdowns, encouragement, and hints | Marda and Thorat (2023) |
| Elevator, Firefighters, Apple farmer, Highway, Ferry, Shooting cans, Recycle, Chicken and worm, Get green, and Dinner | Score, performance, levels of difficulty, tasks, feedback, and progression | Kuo et al. (2023) |
| VR shooter, Slash FRVR, Ping Pong VR, and Snow strike VR | Score, tasks, feedback, time, and obstacles/enemies | Kamatchi et al. (2023) |
| "Phiby's Adventure" mini-games (Chop the wood, Row the boat, and Climb the tree) | Time, levels of difficulty, tasks, and feedback | Peláez-Vélez et al. (2023) |
| MindPod dolphin/Shark punch | Tasks, progress tracking, and levels of difficulty | Stockley & Christian (2022) ; Quarles (2015) |
| Pong | Two modes (multiplayer, player vs. PC), score, dynamic difficulty adjustment | Goršič et al. (2017) |
| Mini-games: Space race, Fish frenzy, and Pop clap | Score, time, feedback, levels of difficulty, and precision evaluation | Allegue et al. (2021) |
| Breakout 3D | Time, score, performance, and multiplayer | House et al. (2016) |
| Card island | Time, score, performance, and multiplayer | House et al. (2016) |

(*Continued*)

TABLE 3 Continued

| Game name | Element | Article |
|---|---|---|
| Musical drums | Time, score, performance, and multiplayer | House et al. (2016) |
| Kites | Time, score, performance, and multiplayer | House et al. (2016) |
| Geometrical figures games (Triangle, Square, Circle, and Spheroids) | Time, performance, and levels of difficulty | Abdul Rahman et al. (2017); Cameirão et al. (2010) |
| Plank game and Ball dodging | Time and performance | Avola et al. (2019) |
| Cannon shooting | Time and dynamic difficulty adjustment | Lin et al. (2017) |
| Sports (Tennis, Basketball, Canoe paddling, Ball throwing, Table tennis, Horse racing, Scuba diver, Darts, and Boxing) | Time, levels of difficulty, score, powerups, obstacles, competition, hints, feedback, countdowns, encouragement, character selection, high score, rankings, progress, and challenges | Salisbury et al. (2020); Dubey & Manna (2019); Lee et al. (2018); Luo et al. (2021); Kaur et al. (2020); Costa et al. (2020); Tsoupikova et al. (2016); Alexandre et al. (2019); Kilbride et al. (2018); Zirbel et al. (2018) |
| Touch balloons/Collect stars (catching/touching games) | Tasks, score, levels of difficulty, time, feedback, and progression | Benrachou et al. (2020); Homola et al. (2022); Amin et al. (2024) |
| Buzzwire | Levels of difficulty, trials, feedback, and randomization | Christou et al., 2018a; Christou et al., 2018b |
| Mirror-therapy mini-games | Performance and feedback | Stephenson et al. (2020) |
| Real-life scenarios mini-games (Hand washing, Drink pouring, Playing piano, Animal petting, Chasing butterflies, Catching snowflakes, Picking fruits from trees or tables, Picking vegetables from the ground, Moving objects, Lifting a barbell, Returning a book, Painting, Cooking, and Dishwashing) | Score, time, tasks, feedback, levels of difficulty, and precision evaluation | Allegue et al. (2021); Rojo et al. (2022); Lee and Cha (2022); Huang et al. (2017); Dias et al. (2019); Shahmoradi et al. (2021); Bouatrous et al. (2023); Bouatrous et al. (2024) |
| Whack-a-mole | Levels of difficulty, scores, modes, no penalties, and feedback | Paraense et al. (2022); Amorim et al. (2023) |
| Flying bird/Spaceship | Levels of difficulty and obstacles/enemies | Huang et al. (2017) |
| Moving cup | Levels of difficulty, real-time feedback, and progress tracking | Hoda et al. (2015) |
| Circus challenge, Rabbit chase, Arrow attack | Implementation of game design patterns: achievers, socializers, free spirits, etc. Feedback (points, badges, and leaderboards) | Holmes et al. (2015) |
| Pongoal, Holidays jogging, Coin frenzy, Pac-man, and Solitaire | Feedback, score, progress tracking, and challenges | Kilbride et al. (2018) |
| Honey pot guard | Feedback, progress tracking, and levels of difficulty; | Choi & Paik (2018) |
| Space shooter | Feedback, score, progress tracking, and challenges | Kilbride et al. (2018); Feng et al. (2020); Shahmoradi et al. (2021) |
| Guiding a sphere through pipes | Feedback, score, progress tracking, and challenges | Shahmoradi et al. (2021) |
| Walking on the ground, Walking on a glass bridge, Axe throwing, Collecting coins, Ball swinging, Step tracking, and Memory game | Feedback, progress tracking, challenges, and levels of difficulty | Bovim et al. (2021) |

score tracking to engage participants. Another gamification element, *dynamic difficulty adjustment* (DDA) based on *performance*, motivated the patients to improve their skills. The results show that movement time to intercept the asteroids improved over the training period, accompanied by significant gains in motor impairment and motor function scores. Goršič et al. (2017) also use DDA. Their Pong game's difficulty automatically adapts every 60 s based on the users' performance (the score, in this case). If the user performed very well, the speed of the ball increases and/or the size of the paddle decreases, if not, the speed decreases, and the size of the paddle increases. The process is predefined, with developers setting clear score thresholds for when adjustments must occur. The difficulty adjustment can also be done manually if users request it. DDA is present in Lin et al.'s shooting game (Lin et al., 2017) as well: if the user's score exceeds 80%, the range in which the obstacles appear will be increased, otherwise, it remains constant. Although EEG data are not used for automatic difficulty adjustment, it is useful for monitoring the user's attention and triggering visual or auditory effects if the user is not paying attention to the exercise.

In Stockley and Christian (2022), the MindPod Dolphin virtual game is introduced, featuring a dolphin character controlled by the upper-limb movements of each patient. Specific oceanic elements, lighting, music, and the overall atmosphere contribute to the user's immersion. The user has various tasks to complete, their progress is tracked, and different difficulty modes are available.

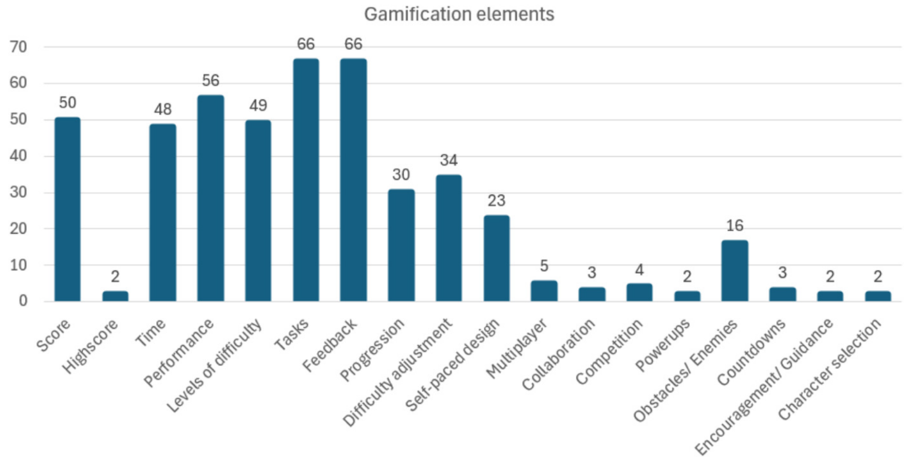

FIGURE 3
Histogram of relevant gamification elements found in the identified articles.

Another popular game is Whack-a-Mole, a classic game in which players must hit moles with a hammer as they pop out of their holes at varying speeds and frequencies. Hoda et al. (2015) present such an approach for chronic stroke rehabilitation, with the game designed with user participation, employing techniques such as online questionnaires and focus groups. Two modes are available: normal and mirror-therapy-based, using only one row of moles. The *difficulty levels* change based on the number of moles and the frequency of their appearance. The evaluation of the patient's performance is based solely on positive feedback, with no penalties or points lost. Tests showed users' preference for natural settings and their skepticism toward the mirrored mode, which was perceived as less intuitive and requiring more time and effort to adapt due to initial disorientation caused by symmetry.

Competition is an intriguing gamification aspect that warrants further research in neurorehabilitation. Goršič et al. (2017) use the classic Pong game for rehabilitation, a popular arcade/PC game in which two players direct a virtual ball using paddles. If one player fails to return the ball, their opponent gains one point. There are two modes available: multiplayer (two human players competing against each other) and player vs. PC (one human player versus an AI-controlled one). Their results show that competition is more relevant when used in at-home rehabilitation than in a clinical setting, as it produces higher enjoyment and motivation.

The utility of competition is also demonstrated by House et al. (2016), in which the multiplayer mode features a tournament between geographically grouped teams with complementary skills (e.g., pairing individuals with low cognitive skills with those who have better cognitive skills). The subjects' preference for playing with a partner is highlighted, with cooperative play leading to faster task completion and higher engagement. Other systems focus on *collaboration*, enabling the creation of VR games in which multiple users can play together within the same virtual scene or even allowing a therapist to practice an exercise with a patient. In Tsoupikova et al. (2016), two scenes provide the context for the games: a kitchen and a living room. The three games developed are: a ball game (two or more participants directing a ball on a table), a retracing game (one user draws a shape in the air, and another must reproduce it), and a food fight game (users throw food at each other in the virtual setting). There is no competition in this study, instead, participants are motivated to execute the correct movements to socialize and collaborate with others.

## 4.1 Popularity, implementation difficulties, and benefits of gamification elements

Within this survey, we created a histogram of the gamification elements (Figure 3), based on their inclusion in the analyzed scientific articles. Although several mechanics are present in almost all the rehabilitation games, some are very scarce. For each gamification element, we will analyze the popularity, implementation difficulty of introducing it into a VR rehabilitation game, and the benefits.

A scoring system is a very popular game mechanic, due to its ease of implementation, and it has very important benefits. Reaching a high score triggers the brain's reward system, keeping the patients motivated to continue their recovery sessions. The score can also represent a metric for observing the patient's progress, as well as a condition for difficulty adjustment, ensuring a balance between the difficulty of the tasks and the user's capabilities. While the score was implemented in a considerable number of the analyzed games, the *high score*, a very popular game mechanic amongst commercial games, is rarely documented in the selected articles. The high score (or leaderboard) introduces the element of historical competition, either with other participants or with one's past self. While many researchers recorded the score for a long period of time, to analyze patients' progress (making it very easy to display a high score), they did not consider the high score useful in the context of neurorehabilitation. However, in our opinion, the high score would further encourage long-term adherence and motivate the patients by showing them the proof of progress and encouraging them to surpass other players.

Another very easy-to-implement mechanic is *time*. While several works compute the time it takes a patient to perform a task, other games are time-bound in the sense that the speed of enemies or obstacles forces the player to perform an action within a certain time frame. In opposition to this mechanic is the *self-paced design*, which allows players to complete the tasks at their own pace, without enforcing time limits or pressure from game-related constraints. While some therapists favor the benefits of time pressure, ensuring an increased efficiency in solving tasks in real life and functioning under stress, others prefer the psychological comfort for their patients. Without time pressure, patients could focus on the quality of their actions and could experiment with various manners of completing a task. Because both mechanics are very easily introduced in a game, they could be used in the same solution, but in different stages of recovery. The self-paced design could be applied in early stages of recovery, in case of severe motor deficits, to avoid frustration. The time limits could be introduced in late stages of recovery, for high-functioning patients who would otherwise become bored. While recording time is implemented in many rehabilitation solutions, *countdowns* are rarely used to avoid inducing a high level of stress in patients.

Most of the analyzed works reported a form of *performance* evaluation, considering various metrics such as the speed or the accuracy of performing a task, range of motion, grip strength, the hit rate in the case of enemies, or the ability to avoid obstacles. The complexity of implementing this mechanic depends on the factors chosen to assess performance. Simple metrics, such as time for performing a task or hit rate, could bring rapid benefits. More complex metrics, such as the quality of movement, would take more time to implement, but would bring long-term benefits, especially in the refinement phase of motor rehabilitation. The difficulty adjustment could also be based on the patient's performance.

Another gamification element, strongly connected with the performance evaluation, is *progression*. As shown in Figure 3, progression is relatively popular. Based on progression information, the game may change the tasks or adjust the difficulty levels. Visible progression can also be used as a motivational factor by providing a sense of achievement in the therapeutic process. While this element can be easily implemented in a game, several researchers preferred to record the progress of the users outside the games, with various clinical tools such as the Fugl–Meyer Assessment (FMA) or the Motor Assessment Scale (MotorAS).

Another very popular game mechanic is the presence of *levels of difficulty*. While some works reported several fixed levels of difficulty (e.g., easy, medium, and difficult), others reported an adaptive increase in difficulty, based on user performance. The levels of difficulty ensure a perfect balance between motivation and comfort. While the same difficulty level would bring frustration to a patient with severe motor deficits, it would probably induce boredom to a patient in the final phase of recovery. These levels can be selected by the patient, by the therapist, or automatically, based on the patient's progress. While the levels of difficulty could be easily implemented with simple algorithms (e.g., increasing the number of enemies and increasing the speed of the obstacles), more complex strategies, such as increasing the intelligence of the enemies, could also represent an alternative.

The *difficulty adjustment* is also connected with other mechanics such as performance, progression, or levels of difficulty. A very important factor in the rehabilitation process, it will be analyzed in more detail in the following section.

Powerups, very popular mechanics in commercial games, are very scarce among rehabilitation games. Powerups could serve as a tool for fatigue or frustration management, appearing when the system detects a drop in patient performance, to prevent the patient from quitting the present rehabilitation session. It could also act as a reinforcement learning element: the game could award the patient with various bonuses based on the time they spend within the rehabilitation sessions, based on the quality of their movements or other performance metrics. Powerups could also be used as compensation for motor limitations. Instead of applying difficulty adjustments, powerups could appear in case patients deal with difficult tasks that cannot be completed by the patient.

The *tasks* are present in all the analyzed articles, representing a core game mechanic. Some games propose daily life tasks (such as picking an apple or hand washing), others are sports-based (with tasks such as playing with a ball), and others imply hitting targets/enemies or avoiding obstacles. Performing certain tasks helps the brain to map activities to real-world situations, enabling transfer of skills from the VR environment to the patient's real life. By focusing on a certain goal, the rehabilitation movement becomes secondary and is performed subconsciously. Tasks also give a purpose to their rehabilitation process, thus maintaining motivation.

Another core gamification element, present in all the analyzed articles, is *feedback*. Any game, whether it be commercial, educational, or rehabilitative, contains a form of feedback. Almost all existing games offer visual feedback: the environment changes when the user moves and objects change their properties (position, form, or color) when the user interacts with them. What is specific to VR games is the first-person view, accompanied by the visualization of an avatar, or of virtual hands. This mechanic brings many benefits to neurorehabilitation by enabling the user's proprioception (awareness of the position and movement of the body): when a person visualizes in VR the result of performing the action of moving their hands, the feedback loop reinforces learning, promoting neuroplasticity. Some of the analyzed games also offer audio feedback, in the form of verbal cues, warnings (very rarely) in case the patient is not performing the tasks as indicated, or sounds that announce the correct completion of an activity. Audio elements are also included to increase immersivity (e.g., oceanic sounds in Stockley and Christian (2022)). While most analyzed works employ visual and audio feedback, another popular form of feedback is haptic, which is also very prevalent in VR games. Such an example is provided by Bae and Park (2023), who attached moving magnetic actuators to the wrists of the patients to generate vibrotactile feedback according to the events from the game. Implementing feedback in video games could be a relatively complex task (especially offering visual feedback in the form of an avatar), but the presence of this gamification element is imperative for the neurorehabilitation process.

Some very beneficial gamification elements, *encouragement and guidance*, are almost nonexistent in the analyzed articles. In Homola et al. (2022), gaze activation turning an arrow green serves as guidance for the user. In Chen et al. (2025), a bird guides the patient to move their hand. These forms of visual feedback are weak examples of guidance. In several articles, guidance and encouragement were offered outside the game by the physiotherapists. While simple forms of encouragement and guidance could be implemented in rehabilitation games, it would be more beneficial (and of course, more difficult) to implement AI-based virtual companions that would offer personalized encouragement and guidance in performing the rehabilitation tasks.

While *multiplayer* games are very popular among players with no motor disabilities, the histogram in Figure 3 shows a very small number of research solutions employing this mechanic. This reduced presence could come from the complexity of implementing multiplayer capabilities, but also from the difficulty of pairing a patient with motor impairments with a collaborator or a competitor (with or without the same motor impairments), and from the complexity of designing collaborative tasks. *Collaboration* and *competition* are the two modes of multiplayer games. As shown in Figure 3, both are rarely present in the analyzed articles (for the reasons mentioned above). However, they offer important benefits for patients. Working in a collaborative environment, in which the users have different skills, could improve the results of the activities. In addition, when partnering with another person, patients often push themselves to perform better, to impress their colleague. On the other hand, competition can shift the patients' focus from the difficulty of the tasks to the desire to win, also encouraging them to push their limits.

A very popular gamification element in commercial games, the presence of *obstacles* or *enemies*, is not very prevalent in rehabilitation solutions. Therapists usually avoid high-adrenaline shooting games or obstacle-evading games that require very fast reaction time and a high level of stress. While these games encourage attention and motor coordination, they could become counterproductive, especially in the first stages of recovery. However, for competitive, high-functioning patients, this mechanic would ensure increased motivation.

Character selection or avatar personalization is an important gamification element in existing commercial games, although the cost of offering personalization could represent an impediment to its adoption for rehabilitation games. Nevertheless, this functionality would surely increase the interest of the patients in playing the games and would offer a more intense sense of presence (especially if the character looked like the user in real life), thus ensuring adherence to the rehabilitation sessions.

This analysis strongly supports the use of gamification principles to enhance various aspects of neurorehabilitation. The most consistent finding is the significant positive impact of gamification strategies on participants' motivation and enjoyment, leading to better performance in regaining motor control. Another finding regarding gamification in neurorehabilitation solutions is that immersive VR is often linked to higher motivation or efficiency, although some patients may prefer third-person views.

## 5 Adaptation to the user

Because neuromotor rehabilitation patients have widely different motor/mobility capabilities, an essential aspect for any practical usage of rehabilitation solutions is the adaptability to each user. Adaptability can encompass aspects such as calibration to the range of motion of the user, various forms of difficulty adjustment, and, to some extent, visual preferences.

Table 4 summarizes our quantitative analysis of the selected articles based on the ability of the games presented in the articles to calibrate the play area to the patients' range of motion, to adjust difficulty, and to modify visual appearance. Details for each system described in the 66 selected articles can be found in Table 5 in the appendix. *Calibration* is essential for effective usage with patients. Neuromotor rehabilitation typically requires specifically designed games or hardware. For best results, these rehabilitation solutions must be calibrated to patients' conditions and needs. Analysis in Table 4 shows that 26 of the 66 analyzed articles have some form of play area calibration, whether automatic or manual. In our view, the calibration process is necessary because patients using exergames for rehabilitation have a vast range of mobility issues, meaning the developed games must be able to adapt to the requirements of a wide variety of patients. We want to highlight that of the 23 articles with no form of calibration, 13 were not tested in any way with post-stroke patients, and another article tested the developed game with only one patient with multiple sclerosis (Quarles, 2015). Of the 26 articles with calibration, 23 were tested with post-stroke patients. Precisely matching this perspective, Dias et al. (2019) explicitly mentioned that in the first iteration conducted with post-stroke patients, they observed that the developed games were unplayable for these patients, leading them to return to the laboratory to adapt the games for this population.

A simple example of calibrating the interactive space available to the patient in the game, based on the patient's range of motion, is provided by Homola et al. (2022). The authors designed the first of the two games presented in the article for lower-limb rehabilitation. This game requires the patient to control a fish within a virtual world to complete a set of missions by extending and bending the knee. At the beginning of the game, the system asks the patient to extend and bend the knee to its minimum and maximum limits to record these limits and then uses those limits when controlling the fish in the virtual world.

Another simple example of game calibration based on a patient's range of motion is described by Bae and Park (2023). In their system, visual representations of specific hand gestures (finger extension, medium wrap, and lateral pinch) are moving toward the patients in a virtual environment. The patients must match the approaching hand gestures generated by the system. Prior to playing the game, each patient performs the three gestures, allowing the system to record their individual motion capabilities. This calibration step ensures that gesture recognition is adapted to the specific motor abilities of each patient.

A more complex calibration process is presented by Cameirão et al. (2010), who developed a game in which the patients must reach out with their hands to touch a set of balls coming toward them. The hand movement takes place on a table, so the balls arrive at the same height level, but at random left-right distances. The system has an initial calibration process to correctly identify the patient's range of motion and calibrate the play area accordingly. Specifically, before starting the game, the system asks the patient to move their hand to four specific points on the table. There are four different points for each hand. The system extracts information such as movement speed, range of motion, and movement initiation time. Additionally, the authors developed an *ad hoc* algorithm to modify the left-right distance within which the balls arrive.

TABLE 4 **Quantitative analysis of the games developed in the selected articles based on their ability to calibrate the play area to the patients' range of motion, adjust difficulty, and modify visual appearance.**

| Type | Calibration | Difficulty adjustment | Visual modification |
|---|---|---|---|
| Automatic | 11 | 14 | 0 |
| Manual | 15 | 20 | 4 |
| None | 23 | 17 | 47 |
| Not relevant | 4 | - | - |
| Commercial product without available information | 9 | 11 | 11 |
| Concept presentation article and no rehabilitation game | 4 | 4 | 4 |

Another complex example that considers the patient's range of motion is presented by Lin et al. (2017). The authors created a game in which the patient must control a cannon's firing process to hit a pirate ship. The patient controls the direction of the cannon by rotating their wrist. Before the game starts, the system asks the patient to perform pronation and supination movements for 5 seconds to record the limits of the patient's range of motion. These limits are then used to determine the position of the pirate ship. It is important to highlight that the game includes an adaptation process for calibration during gameplay. Specifically, the authors implemented an *ad hoc* algorithm that allows the system to adjust the calibration every 10 rounds based on the patient's performance.

Another typical approach involves manually calibrating the exercise area using a control panel operated by a therapist. Dias et al. (2019) developed a platform with three games. The first game requires the patient to lift a barbell by raising and holding their hand above a certain height, the second game asks the patient to pick up a few apples from a table, and the third game has the patient wash a set of virtual dishes. The authors do not provide detailed information but mention that they created a web application for configuring the game parameters. Two of the configurable parameters mentioned, the height at which the patient must raise their hand in the first game and the hand opening required in the dishwashing game, define the calibration of the play area. Avola et al. (2019) developed four games: two for the lower limbs and two for the upper limbs. In the first game designed for upper-limb rehabilitation, the patients hit balls coming toward them, and in the second game, they touched a static ball in front of them with a specific finger of one hand. The authors mention that certain configuration parameters can be set before starting the games. Regarding the calibration of the play area, some of the configuration parameters include the angle at which the balls are launched in the first upper-limb game, and the size of the static ball and the sequence of hands and fingers used to touch the ball in the second upper-limb game.

In some cases, calibration is not necessary. The first game designed by Luo et al. (2021) requires the patient to perform a drumming motion on an imaginary drum with a stick that detects the movement. The speed of drumming on the imaginary drum controls the speed of a horse in a horse racing game. This game does not have an implemented calibration process, but we believe that such a scenario can be executed without any calibration due to the nature of the required movement. Other exceptions are the games designed for the lower limb in the advanced stage of recovery, when patients are regaining balance (Bovim et al., 2021) and posture (Avola et al., 2019). Such games are intended for the advanced stage of rehabilitation and require patients to be able to stand or walk. Because patients need a high range of motion to use the exercises, these games require very little calibration. A final exception is the game developed by Hoda et al. (2015), in which the patient moves their healthy hand, holding the affected hand in it. This way, the patient mobilizes the affected hand. Because the exercise is performed with the healthy hand, this game requires very little calibration.

Difficulty adjustment is specific to each exergame based on the nature of the activities performed. It is important to mention that one form of difficulty adjustment is the modification of the play area (Cameirão et al., 2010; Choi and Paik, 2018; Avola et al., 2019), which places the patient in a situation in which they must perform the exercises close to the limits of their range of motion.

A simple example of difficulty adjustment is represented by increasing the speed of the balls that the patients must touch with their hand to score points (Cameirão et al., 2010) or hit with a virtual paddle controlled by hand position in a multi-user ping pong game (Goršič et al., 2017) or in a 3D breakout game (Salisbury et al., 2020). Another simple example of difficulty adjustment is decreasing the size of the objects that the participants must intercept, while increasing their movement speeds (Rubino et al., 2024). A more complex example of difficulty adaptation is presented by Cameirão et al. (2010), in which the system, in addition to adjusting the speed of the ball, automatically adjusts the interval between ball appearances and the calibration of the play area based on the patient's performance. Another example of difficulty adjustment is provided by Christou et al. (2018a) and Christou et al. (2018b), who have five levels of play with increasing difficulty in their "Buzzwire" game. The difference in difficulty between two consecutive levels is represented by the increase in the height of the curve. In the game presented by Feng et al. (2020), in which the patient controls the actions of a spacecraft through knee movement to destroy *enemy* ships and asteroids, difficulty can be adjusted by configuring the number of enemy ships and asteroids. The Whack-a-Mole game developed by Paraense et al. (2022) offers three difficulty levels, where the number of moles and their frequency of emergence change.

Note from Table 4 that difficulty adjustment is implemented in games presented in 34 articles, whether automatically or manually, compared to the 26 articles that include a play area calibration process. Among the analyzed games, some have only calibration,

TABLE 5 **Qualitative analysis of the games developed in the selected articles based on their ability to calibrate the play area to the patients' range of motion, adjust difficulty, and modify visual appearance.**

| Article | Calibration | Difficulty adjustment | Visual modification | Tested with patients |
|---|---|---|---|---|
| Cameirão et al. (2010) | **Automatic** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Hoda et al. (2015) | Calibration not relevant for task | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| House et al. (2015) | **Automatic** calibration | Commercial solution with no information available | | ✓ |
| Holmes et al. (2015) | Concept presentation article and no rehabilitation game developed | | | |
| Quarles (2015) | No calibration process | No difficulty adjustment | No visual modifications | |
| Tatla et al. (2015) | Concept presentation article and no rehabilitation game developed | | | |
| House et al. (2016) | Commercial solution with no information available | | | ✓ |
| Tsoupikova et al. (2016) | No calibration process | No difficulty adjustment | No visual modifications | ✓ |
| Abdul Rahman et al. (2017) | No calibration process | **Automatic** difficulty adjustment | No visual modifications | |
| Goršič et al. (2017) | No calibration process | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Huang et al. (2017) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Lin et al. (2017) | **Automatic** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Trombetta et al. (2017) | No calibration process | **Manual** difficulty adjustment | **Manual** visual modifications | |
| Choi and Paik (2018) | **Automatic** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Christou et al. (2018a) | No calibration process | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Christou et al. (2018b) | No calibration process | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Kilbride et al. (2018) | Commercial solution with no information available | | | ✓ |
| Lee et al. (2018) | Commercial solution with no information available | | | ✓ |
| Zirbel et al. (2018) | No calibration process | No difficulty adjustment | No visual modifications | |
| Alexandre et al. (2019) | No calibration process | No difficulty adjustment | No visual modifications | |
| Avola et al. (2019) | Calibration is not relevant for the first and second games | **Manual** difficulty adjustment | **Manual** visual modifications | ✓ |
| | **Manual** calibration for the third and fourth games | | | |
| Dias et al. (2019) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Dubey and Manna (2019) | No calibration process | No difficulty adjustment | No visual modifications | |
| Benrachou et al. (2020) | No calibration process | No difficulty adjustment | No visual modifications | |
| Charles et al. (2020) | Concept presentation article and no rehabilitation game developed | | | |
| Costa et al. (2020) | Commercial solution with no information available | | | ✓ |
| Feng et al. (2020) | **Automatic** calibration | **Manual** difficulty adjustment | No visual modifications | |
| Lee et al. (2020) | No calibration process | No difficulty adjustment | No visual modifications | |
| Kaur et al. (2020) | Commercial solution with no information available | | | ✓ |
| Repanovici et al. (2020) | Concept presentation article and no rehabilitation game developed | | | ✓ |
| Salisbury et al. (2020) | **Automatic** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Stephenson et al. (2020) | **Automatic** calibration | Commercial solution with no information available | | |
| Allegue et al. (2021) | Commercial solution with no information available | | | ✓ |
| Bovim et al. (2021) | Calibration not relevant for task | No difficulty adjustment | No visual modifications | |
| Luo et al. (2021) | Calibration not relevant for task | No difficulty adjustment | No visual modifications | ✓ |

(*Continued*)

TABLE 5 Continued

| Article | Calibration | Difficulty adjustment | Visual modification | Tested with patients |
|---|---|---|---|---|
| Shahmoradi et al. (2021) | No calibration process | No difficulty adjustment | No visual modifications | |
| Homola et al. (2022) | **Automatic** calibration for the first game | No difficulty adjustment | No visual modifications | ✓ |
| | No calibration process for the second game | | | |
| Paraense et al. (2022) | No calibration process | **Manual** difficulty adjustment | No visual modifications | |
| Rojo et al. (2022) | No calibration process | No difficulty adjustment | No visual modifications | |
| S. A. Lee and Cha (2022) | Commercial solution with no information available | | | ✓ |
| Stockley and Christian (2022) | Commercial solution with no information available | | | |
| Amorim et al. (2023) | No calibration process | **Manual** difficulty adjustment | No visual modifications | |
| Bae and Park (2023) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Bouatrous et al. (2023) | **Automatic** calibration process | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Chen et al. (2023) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Gao et al. (2023) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Kamatchi et al. (2023) | Commercial solution with no information available | | | ✓ |
| Kuo et al. (2023) | **Manual** calibration | **Manual** difficulty adjustment | **Manual** visual modifications | ✓ |
| Marda and Thorat (2023) | No calibration process | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Masmoudi et al. (2023) | No calibration process | **Manual** difficulty adjustment | **Manual** visual modifications | ✓ |
| Peláez-Vélez et al. (2023) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Aguilera-Rubio et al. (2024) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Amin et al. (2024) | No calibration process | No difficulty adjustment | No visual modifications | ✓ |
| Bedendo et al. (2023) | **Automatic** calibration process | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Bouatrous et al. (2024) | **Automatic** calibration process | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Castillo et al. (2024a) | **Manual** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Castillo et al. (2024b) | **Manual** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Everard et al. (2024) | No calibration process | No difficulty adjustment | No visual modifications | ✓ |
| Korkusuz et al. (2024) | No calibration process | **Manual** difficulty adjustment | No visual modifications | ✓ |
| Kowsalya et al. (2024) | No calibration process | No difficulty adjustment | No visual modifications | |
| Liu et al. (2024) | No calibration process | **Manual** difficulty adjustment | No visual modifications | |
| Munoz-Novoa et al. (2024) | **Manual** calibration | No difficulty adjustment | No visual modifications | ✓ |
| Rubino et al. (2024) | **Manual** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Tan et al. (2024) | **Manual** calibration | **Automatic** difficulty adjustment | No visual modifications | ✓ |
| Zuki et al. (2024) | No calibration process | **Automatic** difficulty adjustment | No visual modifications | |
| Chen et al. (2025) | **Manual** calibration | **Manual** difficulty adjustment | No visual modifications | ✓ |

while others have only difficulty adjustment. The fact that more articles feature difficulty adjustment than calibration, with 12 of them having only difficulty adjustment without calibration, is because difficulty adjustment is a common approach in many traditional computer games. On the other hand, play area calibration is a process almost specifically tailored to patients with neuromotor issues, stemming from the nature of the users' range of motion limitations.

One important aspect of difficulty adjustment is the nature of the process, whether automatic or manual. Table 4 shows that of the 34 articles addressing difficulty adjustment, 20 employ a manual process, and only 14 apply an automatic method. This aligns with the number of articles that perform a calibration process, where 15 of 26 works use a manual process and only 11 use an automatic one. It is important to mention that we considered a game to have a manual difficulty adjustment process, even if there are multiple predefined game levels with different difficulties. We considered that if the levels are predefined, even if they are automatically sequenced, the game still has a manual difficulty adjustment process because the system does not adapt automatically to the patient's performance. The reason more articles use manual adjustment than automatic adjustment is also that many computer games have a manual difficulty control system. Another important observation regarding this aspect is that articles with a manual calibration process also inherently have a manual difficulty adjustment process (Huang et al., 2017; Avola et al., 2019; Dias et al., 2019). This is because the ability to manually modify the calibration also implicitly allows for difficulty adjustments. A final observation is that hybrid approaches for difficulty adjustment are also an option. Goršič et al. (2017) describe a system that assesses the performance of the two patients playing ping pong and adjusts the ball speed based on their performance. Additionally, they can verbally request the observer to adjust this speed, and they can make this change manually.

A final approach to game adjustment for patients that we have identified is the ability to make *visual modifications*. This approach is important from our perspective, but because the research field is still developing, it has been omitted in most articles. Only 4 of 66 articles implemented a manual process for modifying the visual appearance. In the game presented by Trombetta et al. (2017), the system allows the patient to choose their avatar from the options of male or female. Avola et al. (2019) implemented the process of selecting ball colors for the first of the two upper-limb rehabilitation games presented in their article.

After analyzing the elements related to the adaptability to the user, several trends were observed. First, calibration is essential for the effective rehabilitation of motor functions, 26 of 66 analyzed articles included some form of calibration. What stands out is the fact that 23 of these 26 studies included pilot testing with post-stroke patients, demonstrating the practical need for calibration. Difficult adjustment, also a form of gamification, is very important in the neurorehabilitation process, not only for motivation and engagement, but to ensure progress in recovering the motor functions. Regarding visual alterations to the environment or to the user interface, this area is emerging and currently underdeveloped, as demonstrated by the very small number of approaches (4 of 66). Visual modifications represent a nice-to-have functionality, positively impacting the user experience, but are not a "must have" in the neurorehabilitation process.

# 6 Evaluation of VR studies

The selected articles are remarkably diverse in their goals and evaluation methods, ranging from presentations of technical details to protocol descriptions or pilot implementations with actual users (healthy individuals, patients, and therapists). Among the 66 articles, 8 performed no evaluation, 11 evaluated their system only with healthy subjects or physicians, and 47 conducted evaluations that included sufferers (people with neuromotor conditions), either with (15) or without (32) control groups. This section highlights some trends in the evaluation of VR studies regarding types of participants (healthy individuals, therapists, post-stroke patients, and patients divided into intervention and control groups) and evaluation metrics. A detailed analysis for each article is provided in Table 6 of the appendix, specifying the number of patients in the conducted studies, the number of healthy individuals who tested the system, and whether a study with a control group was undertaken. Table 7 provides a list of the metrics frequently used in evaluations, with an acronym (if it exists), the references in literature, and a brief description for each metric.

## 6.1 Types of participants in evaluations

### 6.1.1 Evaluation with healthy patients

A series of pilot implementations used only healthy subjects, people familiar with post-stroke limb impairments (but not suffering from motor impairments), or therapists, focusing more on usability, feasibility, and motivational impact than on clinical efficacy in patients. Abdul Rahman et al. (2017) demonstrate the improvements in movement that can occur through repetition. Rojo et al. (2022) tested their system only with physiotherapists to gather opinions on the usefulness of the FarmDay VR system. Experts also noted that exercises involving finger movements were unsuitable with controllers, suggesting a need for further investigation into new hand-tracking capabilities of VR systems. The pilot study by Trombetta et al. (2017) conducted a comparative evaluation with 10 older healthy patients to examine the differences between using a gamified system with a head-mounted device versus exercising in front of a Smart TV. Even though patients felt somewhat more comfortable with a Smart TV, the results showed good acceptance of VR gamified rehabilitation.

Zirbel et al. (2018) conducted a survey of 73 respondents, both healthy individuals and those familiar with post-stroke upper-limb impairments, for a usability assessment of the VRehab device. The Physio Wear system (Alexandre et al., 2019) was piloted with only two healthy male participants. In the article by Lee et al. (2020), five healthy individuals participated in the study and tested three games across three rehabilitation sessions. In the study by Bovim et al. (2021), a VR walking game was tested on 29 healthy young adults who wore an accelerometer on the lower back to capture gait parameters. The study by Zuki et al. (2024) highlights the importance of gamification, progression, and visual elements in VR rehabilitation games. Two variants of the same pick-and-place game were developed: a minimal version with limited gamification elements, and an augmented version incorporating gamification elements, progression, and enriched visuals. The games were evaluated with 25 healthy individuals, all nursing students. The study used the Intrinsic Motivation Inventory (IMI) questionnaire to measure intrinsic and extrinsic motivation. The results show that the enriched variant had a significant positive impact on participant motivation.

### 6.1.2 Evaluation with healthy and post-stroke users

While some studies performed only usability evaluations with healthy subjects, and other articles focused only on post-stroke

TABLE 6 Analysis of each article, specifying the number of patients in the studies conducted by the authors, the number of healthy individuals who tested the system, and whether a study with a control group was undertaken.

| Article | Post-stroke patient | Healthy tester | Control group |
|---|---|---|---|
| Cameirão et al. (2010) | 21 | 20 | - |
| Hoda et al. (2015) | 3 | - | - |
| House et al. (2015) | 10 | - | 3/10 patients in the control group |
| Holmes et al. (2015) | - | - | - |
| Quarles (2015) | 1 patient with multiple sclerosis | - | - |
| Tatla et al. (2015) | - | 10 | - |
| House et al. (2016) | Not mentioned—tournament of four teams | - | - |
| Tsoupikova et al. (2016) | 15 | - | - |
| Abdul Rahman et al. (2017) | - | 5 | - |
| Goršič et al. (2017) | 15 | - | - |
| Huang et al. (2017) | 8 | - | - |
| Lin et al. (2017) | 12 | - | 12 patients in 3 groups |
| Trombetta et al. (2017) | - | 10 | - |
| Choi and Paik (2018) | 24 | - | 12/24 patients in the control group |
| Christou et al. (2018a) | 11 | 18 | - |
| Christou et al. (2018b) | 6 | 18 | - |
| Kilbride et al. (2018) | 30 | - | - |
| Lee et al. (2018) | 30 | - | 15/30 patients in the control group |
| Zirbel et al. (2018) | - | 6 | - |
| Alexandre et al. (2019) | - | 2 | - |
| Avola et al. (2019) | 92 | - | - |
| Dias et al. (2019) | 12 | - | - |
| Dubey and Manna (2019) | - | 1 | - |
| Benrachou et al. (2020) | - | 13 | - |
| Charles et al. (2020) | - | - | - |
| Costa et al. (2020) | 11 | - | - |
| Feng et al. (2020) | - | - | - |
| Lee et al. (2020) | - | 5 | - |
| Kaur et al. (2020) | 34 | - | 17/34 patients in the control group |
| Repanovici et al. (2020) | 1 patient with hemiparesis | - | - |
| Salisbury et al. (2020) | 1 | - | - |
| Stephenson et al. (2020) | - | - | - |
| Allegue et al. (2021) | 1 | - | - |
| Bovim et al. (2021) | - | 29 | - |
| Luo et al. (2021) | 11 | - | - |
| Shahmoradi et al. (2021) | 10 | 20 | - |

(*Continued*)

TABLE 6 Continued

| Article | Post-stroke patient | Healthy tester | Control group |
|---|---|---|---|
| Homola et al. (2022) | 1 | - | - |
| | 14 | - | - |
| Paraense et al. (2022) | - | 10 | - |
| Rojo et al. (2022) | - | - | - |
| S. A. Lee and Cha (2022) | 20 | - | 10/20 patients in the control group |
| Stockley and Christian (2022) | - | - | - |
| Amorim et al. (2023) | 8 | - | - |
| Bae and Park (2023) | 1 | 11 | - |
| Bouatrous et al. (2023) | 11 | - | - |
| Chen et al. (2023) | 50 | - | 25/50 patients in the control group |
| Gao et al. (2023) | 11 | - | 6/11 patients in the control group |
| Kamatchi et al. (2023) | 8 | - | - |
| Kuo et al. (2023) | 37 | | 18/37 patients in the control group |
| Marda and Thorat (2023) | 32 | - | 16/32 patients in the control group |
| Masmoudi et al. (2023) | 20 | - | - |
| Peláez-Vélez et al. (2023) | 24 | - | 12/24 patients in the control group |
| Aguilera-Rubio et al. (2024) | 36 | - | 18/36 patients in the control group |
| Amin et al. (2024) | 52 | - | 26/52 patients in the control group |
| Bedendo et al. (2023) | Not mentioned, patients were described as being “hemiparetic” and “suffering from cognitive impairments” | 60 | - |
| Bouatrous et al. (2024) | Not mentioned | - | - |
| Castillo et al. (2024a) | 10 | - | - |
| Castillo et al. (2024b) | 10 | - | - |
| Everard et al. (2024) | 21 | 21 | - |
| Korkusuz et al. (2024) | 25 | - | 12/25 patients in the control group |
| Kowsalya et al. (2024) | - | - | - |
| Liu et al. (2024) | 102 | - | 34 |
| Munoz-Novoa et al. (2024) | 6 | - | - |
| Rubino et al. (2024) | 26 | 24 | - |
| Tan et al. (2024) | 12 | - | - |
| Zuki et al. (2024) | - | 25 | - |
| Chen et al. (2025) | 21 | - | - |

TABLE 7 **Outcome measures commonly used in the evaluation of stroke patients during VR rehabilitation.**

| Metric | Brief description | Article |
|---|---|---|
| Fugl–Meyer Assessment (FMA) (Fugl-Meyer et al., 1975; Gladstone et al., 2002) | Stroke-specific tool used to evaluate and measure motor function, balance, sensory function, range of motion of joints, and joint pain | Huang et al. (2017); Chen et al. (2023); Gao et al. (2023) |
| Fugl–Meyer Assessment for Upper Extremity (FMA-UE) (Fugl-Meyer et al., 1975; Gladstone et al., 2002) | Subset of FMA; it focuses exclusively on evaluating motor recovery and function in the upper extremities (shoulder, elbow, forearm, wrist, and hand) | Allegue et al. (2021); Amin et al. (2024); Rubino et al. (2024); Kuo et al. (2023); Kamatchi et al. (2023) |
| Fugl–Meyer Assessment-Lower Extremity (FMA-LE) (Fugl-Meyer et al., 1975; Gladstone et al., 2002) | Subset of FMA; it focuses exclusively on evaluating motor recovery and function in the lower extremities | Liu et al. (2024) |
| Motor Assessment Scale (MotorAS) (Dean and Mackey, 1992; Carr et al., 1985) | Stroke-specific tool used to assess everyday motor function. Instead of evaluating the performance of isolated patterns of movement, it provides a task-oriented evaluation approach | Huang et al. (2017) |
| Motor Activity Log (MAL) with variant MAL-30 (Taub et al., 1993) | Measure of an individual's everyday performance. It is obtained through a semi-structured interview to assess the amount of use and the quality of movement of a patient in their home | Allegue et al. (2021) |
| Action Research Arm Test (ARAT) (Yozbatiran et al., 2007) | Assessment tool designed to evaluate upper-limb function (grasp, grip, pinch, and gross arm movements) | Hoda et al. (2015); Amin et al. (2024); Aguilera-Rubio et al. (2024) |
| Active Range of Motion (AROM) | The range through which a joint can be moved by a patient's voluntary muscle effort | Chen et al. (2023); Kuo et al. (2023) |
| Wolf Motor Function Test (WMFT) (Wolf et al., 2001) | Standard assessment designed to evaluate upper extremity motor function in individuals with stroke or traumatic brain injury. It measures the speed and quality of movement | Chen et al. (2023); Rubino et al. (2024) |
| EQ-5D-5L questionnaire (Herdman et al., 2011) | Questionnaire measuring health-related quality of life (QoL). It consists of two components: the descriptive system (assesses mobility, self-care, usual activities, pain/discomfort, and anxiety/depression), and the EQ Analogue Scale, where patients self-indicate their overall health level on a scale from 0 to 100 | Chen et al. (2023) |
| Treatment Self-Regulation Questionnaire (TSRQ), with its variant, TSRQ-15 (Levesque et al., 2007) | This questionnaire introduces a general approach for evaluating autonomous regulation and controlled regulation for patients | Allegue et al. (2021) |
| Modified Ashworth Scale (ModifiedAS) (Bohannon and Smith 1987) | Tool for assessing muscle spasticity | Chen et al. (2023); Peláez-Vélez et al. (2023) |
| System Usability Scale (SUS) (Brooke, 1996) | 5-point Likert scale questionnaire for evaluating the usability of various systems, especially software or digital devices | Abdul Rahman et al. (2017); Bouatrous et al. (2023); Bouatrous et al. (2024); Bedendo et al. (2023) |
| Intrinsic Motivation Inventory (IMI) (Ryan and Deci, 2000) | Questionnaire that assesses individuals' subjective experiences related to a specific activity, focusing mainly on intrinsic motivation | Goršič et al. (2017); Bouatrous et al. (2023); Bouatrous et al. (2024); Zuki et al. (2024) |
| Virtual Reality Neuroscientific Questionnaire (VRNQ) (Kourtesis et al., 2019) | Tool used to assess the quality of the VR software and the intensity of VR-induced symptoms, such as nausea, dizziness, and fatigue | Castillo et al. (2024b) |
| Immersive Tendencies Questionnaire (ITQ) (Witmer and Singer, 1998) | Self-report questionnaire to assess the propensity of an individual to become immersed in mediated environments (VR, video games, movies, and books) | Castillo et al. (2024b) |
| Box and Block Test (BBT) (Mathiowetz et al., 1985a) | Assessment designed to measure unilateral gross manual dexterity. The assessment involves patients moving as many small wooden cubes as they can into a box within a 60-s period | Lee and Cha (2022); Amin et al. (2024); Everard et al. (2024); Aguilera-Rubio et al. (2024); Kuo et al. (2023) |
| Stroop Test (ST) (Jensen, 1965) | It measures recognition reaction times to colors when the words and their colors are not in agreement | Lee and Cha (2022) |
| Barthel Index (BI) and Modified Barthel Index (MBI) (Mahonery and Barthel, 1965) | Assessment tool that evaluates a person's ability to perform activities of daily living (ADLs) independently. MBI assesses 10 domains of daily functioning: feeding, bathing, personal hygiene, dressing, bowel control, bladder control, toilet use, transfers, mobility, and stair climbing | Amin et al. (2024); Korkusuz et al. (2024); Gao et al. (2023); Marda and Thorat (2023) |

(*Continued*)

TABLE 7 Continued

| Metric | Brief description | Article |
|---|---|---|
| Stroke-Specific Quality of Life (SSQOL) (Williams et al., 1999) | Self-report instrument that assesses health-related quality of life in individuals who have experienced stroke. It offers insights into both physical and psychosocial aspects of recovery | Amin et al. (2024) |
| Berg Balance Scale (BBS) (Badke et al., 2004; Berg et al., 1992; Usuda et al., 1998; Wee et al., 1999) | Tool designed to assess an individual's balance activities and risk of falling. BBS evaluates both static and dynamic balance through a series of functional tasks commonly encountered in daily life | Liu et al. (2024); Marda and Thorat (2023); Peláez-Vélez et al. (2023) |
| Timed Up-and-Go Test (TUGT) (Mathias et al., 1986) | Assessment designed to evaluate a person's mobility, balance, waking ability, and risk of falling | Liu et al. (2024); Korkusuz et al. (2024) |
| 6-m walking test (6MWT) (ATS Statement, 2002) | Measures the distance an individual can walk in 6 minutes on a flat, hard surface. It evaluates submaximal aerobic capacity and endurance | Liu et al. (2024) |
| Functional Reach Test (FRT) (Duncan et al., 1990, Weiner et al., 1992) | Assessment that evaluates an individual's stability and balance by measuring how far they can reach forward without moving their feet | Korkusuz et al. (2024) |
| Disabilities of the Arm, Shoulder and Hand (DASH) (Beaton et al., 2001a; Beaton et al., 2001b) | Self-reported questionnaire that measures the physical function and symptoms in individuals with musculoskeletal disorders of the upper limb | Aguilera-Rubio et al. (2024) |
| Performance-Oriented Mobility Assessment (POMA)/Tinetti Balance Scale (Tinetti et al., 1986) | Evaluates an individual's balance and gait abilities | Marda and Thorat (2023); Peláez-Vélez et al. (2023) |
| Stroke Impact Scale (SIS), with variant SIS-16 (Duncan et al., 1999; Duncan et al., 2003) | Self-report questionnaire that assesses the effects of stroke on an individual's health and quality of life. The questions are divided into eight domains: strength, hand function, activities of daily living, mobility, communication, emotion, memory and thinking, and social participation | Allegue et al. (2021); Kuo et al. (2023) |
| Daniels and Worthingham Scale (Daniels et al., 2013) | Evaluates the function and strength of individual muscles or muscle groups | Peláez-Vélez et al. (2023) |
| Motricity Index (MI) (Demeurisse et al., 1980) | Evaluates limb strength in individuals recovering from stroke. It focuses on specific movements in both upper and lower extremities | Peláez-Vélez et al. (2023) |
| Nine-Hole Peg Test (9HPT) (Mathiowetz et al., 1985b) | A standardized test that assesses finger dexterity. The patient is asked to take pegs from a container and place them into holes on a board | Kaur et al. (2020) |
| 11-point visual analog scale (Langley and Sheppeard, 1985) | A metric that evaluates pain | Chen et al. (2023) |
| Difficulty Adjusted Performance Index (DAPI) (Castillo et al., 2024a) | A metric designed to normalize performance scores based on game-specific mechanics and difficulty levels | Castillo et al. (2024a) |
| NASA-task load index (TLX) questionnaire (Hart, 2006) | A questionnaire that evaluates user experience | Bedendo et al. (2023) |
| Jamar hydraulic dynamometer | A tool that assesses grip strength | Aguilera-Rubio et al. (2024) |
| Trunk Control Test (Duarte et al., 2002) | A test that is performed on a bed, consisting of four tasks: rolling to the weak side, rolling to the strong side, balance in a sitting position on the edge of the bed, sitting up from lying down | Peláez-Vélez et al. (2023) |
| Surface electromyography (sEMG) | A tool that detects muscle activation | Tan et al. (2024); Gao et al. (2023); Kamatchi et al. (2023) |

patients, several research works presented an iterative development strategy, first testing with healthy users and then performing evaluations with post-stroke users. Other researchers conducted both performance and usability testing, with either patients or healthy users and therapists.

Christou et al. (2018a) and Christou et al. (2018b) compared healthy and affected subjects through two sets of experiments using a VR game, collecting data such as time, collisions, deviation from the center of the wand, and average speed. The first group, comprising 18 healthy subjects, aimed to validate certain aspects related to the safety of the testing procedure before testing with stroke patients. They compared stereo with monocular vision and performed the exercise with both hands. The results showed significantly better performance with stereovision and the dominant hand. In the second study, which involved six patients with hemiparesis following a stroke, users reported that rotation tasks were more difficult than translation tasks. Additionally, the head-mounted display (HMD) was not found to be uncomfortable, did not cause nausea, but did present some focus issues.

Shahmoradi et al. (2021) surveyed nine physiotherapists and eleven game designers with a survey-based questionnaire to acquire feedback on the exercises. Subsequently, 10 patients with chronic stroke, but without neurological or orthopedic disorders of the upper limbs, played five games three times a week for 4 weeks. Experts who participated in the survey noted that the use of in-game incentives and bonuses was effective in enhancing motivation.

The study by Cameirão et al. (2010) involved a total of 41 participants (20 healthy individuals and 21 stroke patients) who performed various tasks with the Rehabilitation Gaming System (RGS). This led to the development and validation of a personalized training module and demonstrated the transfer of skills between virtual and physical environments. The usability evaluation indicated that stroke patients highly embraced the RGS as a tool for rehabilitation.

Bedendo et al. (2023) introduce a home-based VR rehabilitation system, exploring its feasibility and efficacy in stroke rehabilitation programs. The system was evaluated with 60 participants, focusing on user experience, immersion, and potential VR sickness. Additionally, an initial study to assess the general user experience using the System Usability Scale (SUS) was conducted with two patient groups: hemiparetic individuals and those with cognitive impairments. The results indicate positive user perception, highlighting the potential of VR applications in the future development of home-based rehabilitation programs.

Everard et al. (2024) evaluated multiple variants of the Box and Block Test (BBT) to assess their validity and usability in measuring post-stroke manual dexterity. The study examined four versions: the traditional BBT, a VR variant using controllers (BBT-VR-C), a VR variant using hand tracking (BBT-VR-HT), and a mixed-reality variant (MD-MR). The aim was to determine whether the digital variants provide reliable and valid assessments for stroke rehabilitation. The study included 21 stroke patients with hemiparesis and 21 healthy control participants. The SUS questionnaire was used to assess the usability of the tests. Additionally, five therapists familiar with BBT completed questionnaires evaluating multiple aspects of the tests, including the difficulty of opening the hand, gripping the cube, and maintaining the grip. Results showed that BBT-VR-HT and BBT-MR had similar difficulty levels to the traditional BBT, while BBT-VR-C was more difficult. The difficulty ratings of BBT-VR-HT and MD-MR were classified as excellent. The study concludes that all VR and MR variants of BBT (BBT-VR-C, BBT-VR-HT, and MD-MR) are valid, reliable in the short term, and usable tools for assessing post-stroke manual dexterity.

Rubino et al. (2024) proposed a gamified system for stroke rehabilitation in which patients control an on-screen spaceship using hand movements to intercept moving asteroids. The study recruited 40 stroke patients and 30 healthy older adults as a control group. The study assessed the mean movement time to successfully intercept asteroids, alongside motor impairment and motor function using the Fugl–Meyer Assessment for Upper Extremity (FMA-UE) and Wolf Motor Function Test (WMFT) before and after the 10 training sessions. Results indicated improvements in movement time and FMA-UE, and WMFT scores.

Bae and Park (2023) proposed a VR-based hand rehabilitation system featuring a gesture-controller rhythm game. They evaluated the system's impact on brain activity using functional near-infrared spectroscopy (fNIRS). In addition to measuring cortical activation, the study measured the success rate of the participants matching the gestures generated by the game and evaluated user experience through a 5-point Likert scale survey covering engagement, presence, and motivation. The study included 11 healthy participants and one stroke survivor with mild left-sided hemiplegia. The success rate of the healthy subjects ranged from 68.6% to 99.3% with a mean of 90% (SD = 10.7%). The success rate of the stroke patient was 79.6%. fNIRS data revealed increased cortical activation across all regions of interest in both healthy individuals and the stroke survivor. The survey indicated that participants found the system engaging, felt a sense of presence, and were motivated to continue using the system for their training. Overall, the findings indicate that the system successfully activates brain areas associated with motor planning/execution, multisensory integration, and attention.

### 6.1.3 Control groups

From the analyzed articles, we observed that 47 research works focused on patients, conducting evaluation studies with people suffering from neuromotor disabilities. However, 32 of these lacked a control group, limiting the generalizability of therapeutic efficacy. With more robust designs, 15 studies included a control group, typically comparing the VR intervention against traditional therapy or sham treatments.

In several studies, the results demonstrate the superiority of neurorehabilitation strategies involving VR, in terms of efficiency, compared to classical rehabilitation. For example, Lin et al. (2017) divided 12 patients into three groups: one receiving classical rehabilitation, one utilizing virtual reality with a custom motion-tracking device, and one using combined virtual reality, a custom motion-tracking device, and an EEG device. Although all groups showed improvements in scores, hits, and motor function, the best results were achieved by the third group, where the EEG was used to generate stimuli in the VR environment to keep the user focused when a lack of concentration was detected. The primary outcome of the study by Choi and Paik (2018) was also improved motor function, with secondary results, including enhanced upper-limb function and high user satisfaction for VR rehabilitation, compared to conventional therapy. In the study by Lee and Cha (2022), an experimental group received transcranial direct current stimulation (tDCS) and virtual reality, while the control group received sham tDCS (a procedure that mimics the tingling sensation given by current stimulation) and virtual reality. There were significant differences between the experimental group and the control group in the Box and Block Test (BBT) and in the Stroop Test (ST) evaluation metrics. Kaur et al. (2020) included 30 patients who were divided into two groups: one group received therapy with virtual reality games, while the other group received neurodevelopmental treatment. Results were more favorable for patients in the virtual reality game therapy group. In the study by Chen et al. (2023), a suite of exergames was developed as part of a VR-based exercise system for post-stroke upper-limb rehabilitation. Fifty stroke patients participated in the study and were randomly assigned to the intervention group (the proposed VR-based rehabilitation system) or the control group (commercial VR games). The results indicated improvements in most outcomes within both groups, but greater improvement in the intervention group for a certain metric (shoulder abduction active range of motion (AROM)). Marda and Thorat (2023) compared task-oriented training and VR-based training on balance in stroke patients. A total of 32 participants were randomly assigned to two groups: one group received conventional exercises combined with task-oriented training, while the other received conventional exercises alongside VR-based balance training. Results showed that both intervention programs were effective in terms of improving balance. However, the group receiving VR-based training showed greater improvement than the task-oriented training group. Kuo et al. (2023) investigated the effects of the PABLO system, a non-immersive VR-based rehabilitation tool, on upper extremity function in patients with chronic stroke. A total of 37 participants were randomly assigned to either a VR intervention group (n = 19) using the PABLO system or a control group (n = 18) receiving standard rehabilitation. The study concluded that the PABLO-based VR intervention led to improvements in hand function, shoulder and elbow movement, and was perceived by patients as more enjoyable than conventional rehabilitation. Peláez-Vélez et al. (2023) evaluated the effects of combining traditional neurological physiotherapy with a VR-based program in the treatment of patients recovering from stroke. A total of 24 stroke patients participated in the study and were randomly allocated to either an experimental group (n = 12) or a control group (n = 12). The results showed that the combination of VR and traditional physiotherapy significantly improved balance, gait, trunk control, and functional level of gait, even if no significant differences were found in strength and spasticity. Aguilera-Rubio et al. (2024) evaluated the effectiveness of a non-immersive VR system using the Leap Motion Controller to improve upper-limb functionality in individuals with chronic stroke. A total of 36 stroke patients participated, with 18 assigned to the experimental group and 18 to the control group. The results show that the proposed VR system improved grip strength, dexterity, and motor function in patients with chronic stroke. Amin et al. (2024) describe an approach to integrating cognitive engagement within visual feedback for the development of VR rehabilitation games aimed at stroke patients. A total of 56 subacute stroke patients participated in the study, with 26 participants assigned to the experimental group and 26 to the control group. The study concluded that the VR games improved motor functions, dexterity, and enhanced the patients' quality of life and functional independence. The study by Korkusuz et al. (2024) investigates the effectiveness of a non-immersive VR game-based training (nIVRGT) in improving balance, knee hyperextension control, and activities of daily life (ADL) in stroke patients. The study included 25 patients, with 13 assigned to the experimental group and 12 to the control group. The intervention included two non-immersive VR games which focused on knee flexion/extension and weight-bearing activities. The findings indicate that both conventional rehabilitation and nIVRGT combined with conventional rehabilitation resulted in improvements in dynamic balance and knee control. Additionally, nIVRGT was also observed to improve ADL, and was found to be more effective in improving dynamic balance than conventional rehabilitation alone.

Liu et al. (2024) presented a randomized controlled trial study protocol for a 4-week intensive intervention combining VR-based task-oriented training with repetitive transcranial magnetic stimulation (rTMS) to improve balance function and brain plasticity in stroke patients. The proposed system, Virtual Reality Digital Twin Stroke Hemiplegia Rehabilitation and Training System (Beijing NuoYiteng Technology Co., Ltd.), is used for the following rehabilitation games: Fruit catching, Tennis playing, and Obstacle avoidance, each targeting specific balance exercises. The study involved 136 stroke patients, randomly assigned into four equal groups: VR therapy, rTMS therapy, combined VR + rTMS therapy, and a control group receiving traditional balance exercises. The study hypothesizes that the integration of VR with rTMS may lead to significant improvements in both balance function and neuroplasticity among stroke patients compared to either intervention alone.

## 6.2 Evaluation metrics

Analyzing the selected articles, we noted that several studies evaluate the usability of the developed rehabilitation solutions, while others assessed the efficacy of those solutions in helping patients regain motor control. In addition, while some studies applied proprietary measures, most of the articles relied on standardized metrics. While a full list of evaluation metrics, along with their acronyms, descriptions, and studies that used them is provided in Table 7, this sub-section tries to organize the most popular evaluation metrics based on measurement, type of instruments, and body region assessed.

### 6.2.1 Measurement focus

Some metrics, such as the Fugl–Meyer Assessment, are specific to stroke, evaluating impairment and recovery status. Others, such as the Modified Ashworth Scale (MAS) and the Daniels and Worthingham Scale, evaluate muscle strength and tone. Another measurement focus, dexterity and speed, is evaluated with metrics such as the Action Research Arm Test (ARAT), the Box and Block Test (BBT), Disabilities of the Arm, Shoulder and Hand (DASH), and the Nine-Hole Peg Test (9HPT). Balance, stability, and gait are assessed with the Berg Balance Scale (BBS), the Functional Reach Test (FRT), and the Performance-Oriented Mobility Assessment (POMA)/Tinetti Balance Scale. Relating to quality of life, questionnaires such as the Stroke Impact Scale (SIS) and the Stroke-Specific Quality of Life (SSQOL) are used.

### 6.2.2 Type of instrument

Most of the used metrics are performance-based tests that evaluate the users' capacity to perform certain tasks. While many of the studies use standard performance-based tests (FMA, MAS, ARAT, BBS, POMA, Motricity Index (MI), BBT, 9HPT, etc.), other studies use game-specific performance metrics, such as time, distance traveled, rewards, and task accuracy. Other types of instruments are self-report questionnaires, such as Disabilities of the Arm, Shoulder and Hand (DASH), SIS, and SSQOL.

### 6.2.3 Assessed body region

While some of the metrics focus on evaluating the upper limb (ARAT, BBT, DASH, 9HPT, and FMA-UE) and others evaluate the lower limbs (FMA-LE), many metrics evaluate either both upper and lower limbs (FMA and MI) or the whole body (BBS, Functional Reach Test (FRT), and POMA). Among the metrics used, several instruments evaluate specific muscles (DASH and MAS).

A series of conclusions can be drawn from analyzing the evaluation strategies of the selected articles. First, we noted a limited generalization of results due to the small size and heterogeneity of the users included in the studies. Next, even though many articles used standard evaluation metrics, such as FMA, SIS, and SUS, there is a lack of standardized protocols for evaluating VR systems, making it difficult to compare findings across different research works. As previously mentioned, only 15 of the 66 studied articles performed evaluations with control groups. This absence of control groups makes it challenging to attribute any observed improvements solely to the gamified VR strategies. Even though most of the articles included some kind of evaluation, many studies involved a limited number of sessions, with a short duration. This limited exposure may be insufficient to observe significant lasting therapeutic effects from the VR experiences.

## 7 Conclusion

The methodology for this systematic review was based on the PRISMA statement model, adapted to the needs of this study. We started with 4,856 articles extracted from five reputable scientific databases and applied step-by-step exclusion criteria to narrow down to 66 articles analyzed in depth in this study. A limitation of this survey is the filtering and selection of the articles by a single person. However, the clear steps for inclusion and exclusion ensure reproducibility.

The selected articles were then analyzed in Section 3, Section 4, Section 5, Section 6, focusing on aspects such as technologies, games, and gamification, adaptability to patient, and evaluations included in the study.

In terms of technologies, both commercially available and custom devices have proven to be successful, with immersive VR showing superior performance. Custom solutions usually employed optical tracking and IMUs, and robotics was often used in conjunction with VR for physical assistance and guiding. Needs for accessibility, affordability, and ease of use, combined with the latest evolution of VR headsets, have shifted the balance in recent years toward commercial VR headsets.

Regarding games and gamification, our analysis emphasizes them as central components of the VR neuromotor rehabilitation process. The variety of games showcased in Table 3 (Annex 1) demonstrates that a wide range of genres and themes can be successfully used in training. Sports games and mini-games simulating real-world tasks are particularly preferred and frequently featured in many of the selected articles. Variety, specific gamification elements, positive reinforcement, and dynamic difficulty adjustment play crucial roles. Further observations on this topic are

- A wide variety of games is necessary, ranging from very simple ones that stimulate basic movements to real-life scenarios that simulate daily activities.
- A balance between entertainment and rehabilitation objectives is desired and should be explored in future studies.
- Elements such as scores, rewards, and various difficulty levels have been proven to influence both enjoyment and motivation, supporting the long and intensive rehabilitation process.
- Dynamic difficulty adjustment ensures that the training process maintains a balance between challenge and engagement.
- For the games to be motivating and effective, the personal preferences and individual characteristics of the patients should be considered during the design process. The games should involve situations and tasks that patients can easily understand without prior experience with gaming or VR.
- Unlike most traditional gamers, people suffering from neurological disorders prefer positive reinforcement and should not be exposed to negative feedback (Paraense et al., 2022) to maintain motivation.
- We predict that the design of neurorehabilitation games is still in its infancy and will evolve into a distinct research area with specific principles, genres, mechanics, and gamification strategies.

We identified adaptation to the patient as an essential aspect for the success of VR gamified neurorehabilitation, encompassing a comprehensive perspective that includes work area, precision and sensitivity calibration, difficulty adjustment, and even visual modifications. We noted a strong correlation between the adaptability features described in the analyzed systems and the robustness of their evaluations, suggesting that adaptability is crucial for these solutions to be effective for patients. However, only a small number of systems exhibited basic forms of automatic adaptation, highlighting the need for future work to focus on this aspect.

More than half of the analyzed articles conducted evaluations with patients, but all used small patient samples, lacking strong statistical relevance, and only 14 articles included control groups. In most cases, both rehabilitation outcomes and feedback from physiotherapists and patients clearly indicated the usefulness and significant potential of VR training for neurorehabilitation. The results demonstrated significant neuromotor functional improvements and high levels of motivation, especially when compared with or used in combination with traditional therapy. Additionally, the analyzed systems showed distinct advantages, such as increased repetition rates, comfort, and accessibility. These findings provide evidence that gamified VR neurorehabilitation is a likely complement to conventional rehabilitation methods in the near future, with the potential to scale up to meet societal needs.

### 7.1 Future research

As previously mentioned, there is a need for future work to focus on the aspect of automatic adaptation to the user, in terms of calibration, difficulty adjustment, and personalization of visual elements. In addition, there is still a need for large-scale clinical trials to support the development of commercial solutions, identify optimal integration with traditional therapy, and facilitate adoption into gold-standard therapy plans.

An important research direction is also the expansion of the gamification techniques. The analyzed articles included forms of gamification, but most of them lacked personalization based on the recovery stage. In addition, most of these solutions ignored cognitive or motivational problems in patients. How can a recovery plan be adapted if the patient is depressed, or if they also have important cognitive impairments, which often occur in post-stroke situations? There is still no body of knowledge about applying the appropriate gamification techniques, based on the user's profile and various cognitive/motor impairments. Therefore, multidisciplinary research teams (including therapists, psychologists, and VR experts) could bring breakthrough benefits if they focused on this direction.

During our analysis, we also searched for the presence of cognitive elements in the rehabilitation processes. While most of the solutions focus only on neuromotor rehabilitation, they nevertheless employ subconscious cognitive elements such as hand–eye coordination, spatial processing, attention, proprioception, gaze interaction, motor planning, motor imagery (mentally imagining the movement), and reaction speed. Several articles acknowledge the importance of extrinsic cognitive tasks, proposing matching image pairs or memory tasks (Holmes et al., 2015), puzzle solving and memorizing (Holmes et al., 2015), pattern recognition (House et al., 2016), shape recognition (Abdul Rahman et al., 2017), and following rhythmic patterns and remembering musical sequences (Luo et al., 2021). Another very important research direction would be to employ a holistic approach, combining both motor and cognitive rehabilitation, and obtaining a maximum level of immersion (sensorial, cognitive, and emotional/psychological), to ensure long-term adherence for the patients.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

## Author contributions

AlM: Conceptualization, Supervision, Writing – review and editing. IS: Conceptualization, Writing – original draft. AL: Conceptualization, Writing – review and editing. AA: Writing – review and editing. SS: Writing – review and editing. AnM: Conceptualization, Writing – review and editing. VA: Supervision, Writing – review and editing. R-GL: Supervision, Writing – review and editing. DC: Supervision, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Artificial intelligence tools were used solely to assist with English language editing, phrasing, and grammar correction. No AI tools were employed for data analysis, interpretation, or the generation of scientific content.

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## Publisher's note

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