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Personalized eXtended Reality experiences to enhance the rehabilitation process of stroke survivors: A scoping review ☆

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A R T I C L E I N F O

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A B S T R A C T

Stroke affects millions globally, resulting in physical impairments such as paralysis, speech challenges, and cognitive deficits like memory loss. Rehabilitation plays a vital role in recovery, helping regain lost functions, and achieve greater independence, facilitating reintegration into daily life. Despite this, rehabilitation programs rely on standardized approaches that fail to accommodate the unique needs and goals of individual stroke survivors. This lack of personalization can lead to frustration, loss of motivation, and reduced engagement, ultimately hindering recovery and slowing progress. One possible approach to help overcome these challenges is eXtended Reality (XR), offering immersive, adaptable virtual environments. XR enables the creation of dynamic and customizable exercises tailored to the specific needs, abilities, and preferences of each individual. These experiences can be interactive and engaging, improving motivation and fostering active participation compared to traditional methods. XR also allows for real-time tracking and feedback, making the process both more effective and enjoyable. This work contributes to the field by presenting a scoping review on personalized XR experiences for stroke rehabilitation, resulting from an analysis of 39 publications within the SCOPUS database covering the period from 2020 to 2024. The review provides insights into trends, advancements, and challenges, identifying opportunities for future development in this area. By consolidating knowledge in this field, we aim to help guide the development of personalized XR solutions, ultimately improving rehabilitation outcomes and quality of life for stroke survivors and their caregivers.

1. Introduction

Stroke is a leading cause of disability and mortality worldwide, resulting from a disruption in blood flow to the brain, either due to a blocked artery (ischemic stroke) or a ruptured blood vessel (hemorrhagic stroke). This interruption deprives brain cells of oxygen and nutrients, causing cell death and potentially leading to a range of neurological impairments [1–4]. Stroke affects millions of individuals annually, significantly impacting their ability to perform daily activities and diminishing their quality of life. The World Health Organization (WHO) estimates that one in four people will experience a stroke in their lifetime, making it a critical public health concern [5–8].

Beyond its direct impact on survivors, stroke places immense physical, emotional, and financial burdens on caregivers and healthcare professionals. Caregivers often face long-term responsibilities, including assisting with daily tasks, managing medical treatments, and providing emotional support. This can lead to caregiver burnout, stress, and reduced quality of life. Healthcare professionals, on the other hand, are challenged with managing individualized care plans, monitoring

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progress, and addressing the complex needs of stroke survivors, often within constrained healthcare systems [9–12].

Rehabilitation plays a central role in helping stroke survivors regain lost functions and adapt to their new physical and cognitive realities. Traditional rehabilitation methods include physical therapy for restoring motor skills, occupational therapy for relearning everyday tasks, and speech therapy for addressing language and communication difficulties [13–16]. Over time, these interventions aim to enhance neuroplasticity, i.e., the brain's ability to reorganize itself, enabling survivors to recover or compensate for their impairments [17–20].

Despite their importance, existing rehabilitation methods are not without limitations. The repetitive nature of exercises often leads to decreased motivation and engagement, particularly during long recovery periods [21,22]. Survivors may feel isolated due to the lack of a social component, further reducing their commitment to the process [23–25]. Additionally, many programs are not sufficiently individualized, failing to account for the unique challenges, capabilities, and goals of each survivor. These limitations can slow recovery and, in some cases, result in regression, underscoring the need for more innovative and adaptable approaches to rehabilitation [2,26–28].

Emerging technologies like eXtended Reality (XR), which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), have shown promise in addressing some of the challenges of traditional rehabilitation [29–32]. Environments using XR offer immersive and engaging experiences, where survivors can practice motor and cognitive tasks in virtual settings that mimic real-life scenarios. These environments can be tailored to provide immediate feedback, gamification, and adaptive difficulty levels, fostering greater motivation and sustained engagement [33–36].

Moreover, XR aligns well with the needs of stroke rehabilitation by enabling repetitive practice in a controlled, safe environment [15,37–39]. Through gamified tasks and realistic simulations, survivors can work on motor skills, balance, and cognitive functions in ways that feel less monotonous than traditional therapy. Additionally, XR can facilitate social interaction by incorporating multiplayer tasks or connecting survivors with therapists and peers in virtual spaces, addressing the isolation often felt during recovery [40–43].

Despite existing advancements in XR-based rehabilitation, a critical gap in research lies in the area of personalized XR environments for stroke recovery. Personalization has long been recognized as a cornerstone of effective traditional therapy, as each stroke survivor's recovery journey is unique. Yet, current implementations adopt a one-size-fits-all approach, disregarding the individual physiological, emotional, and cognitive needs of each person. By tailoring exercises to the individual's abilities, preferences, and progress, rehabilitation can remain achievable yet challenging, promoting motivation and steady improvement. Without such considerations, XR solutions may struggle to reach their full potential in diverse real-world rehabilitation scenarios [44–47].

Recently, to help better understand the existing methods for implementing the personalization process, a proposal for structuring existing methods has been presented (see Fig. 2), focusing on 5 major types [48] (although as the field matures, others may start to emerge):

- **Rule-based Systems:** Predefined rules adjust the XR experience based on performance data. For instance, if specific task milestones are unmet, the system can lower task difficulty or enhance assistance moving forward;
- **Bio-feedback:** Physiological data from sensors (e.g., heart rate, muscle activity) can drive personalization. High stress or fatigue levels might trigger a calming environment or a task intensity reduction;
- **Behavioral Tracking:** Monitoring movement, posture, and engagement informs when users face frustration or fatigue, enabling task simplifications, motivational boosts, or gamified enhancements;
- **Contextual Adaptation:** External factors like session timing, previous session duration, or user mood enable dynamic adjustments to session structure or intensity;
- **Intelligent Monitoring:** Intelligent algorithms and techniques can analyze data patterns to predict user needs, allowing the system to refine task difficulty and improve its responsiveness over time.

These categories help provide a roadmap for integrating personalization into XR systems, paving the way for more effective and user-centric rehabilitation approaches. Regardless, further information is required to establish a more systematic and holistic understanding of the current state of this field, namely current advancements, consolidating fragmented findings, and identifying both strengths and gaps in existing research. This could offer valuable insights into the effectiveness of various personalization strategies, the role of emerging technologies like data-driven adaptations, and the challenges in implementing these approaches. By synthesizing knowledge, the research community can establish a clearer framework for developing adaptive and individualized rehabilitation methods, enabling the design of more effective solutions tailored to the diverse needs of stroke survivors. Ultimately, better understanding of the field can also guide practitioners and technology developers to create accessible and impactful applications, driving innovation, and improving recovery outcomes for stroke survivors.

This work advances the field by conducting a scoping review of personalized XR in stroke rehabilitation, providing a detailed analysis of current research and solutions. Personalization is paramount for survivors, as tailored approaches address individual impairments, preferences, and goals, ultimately enhancing motivation, engagement, and the effectiveness of rehabilitation [50]. To guide this review, two research questions were established:

"How can eXtended Reality environments be personalized to adapt to stroke survivors' needs during rehabilitation procedures?" and *"How does personalization affect a stroke survivor during rehabilitation activities?"*.

The review seeks to deepen the understanding of the current state of personalized XR applications, identify existing gaps, and offer a structured perspective to inform future innovations in this domain. To achieve these goals, we examined literature published between 2020 and 2024, focusing on studies indexed in the SCOPUS database. An initial search yielded 82 relevant publications, of which 39 met the predefined inclusion criteria following a detailed review. The findings offer valuable insights into the progress and challenges associated with integrating XR into stroke rehabilitation. By conducting the systematization of this information, this review highlights opportunities to improve personalization and engagement in XR-based rehabilitation. This consolidated perspective aims to drive the development of tailored, effective, and immersive rehabilitation tools that enhance recovery outcomes and improve the quality of life for stroke survivors and their caregivers.

The remaining of this paper is organized as follows: Section 2 presents an example of personalized XR. Section 3 details the methodology of the literature review, and Section 4 presents the main insights obtained. Next, Section 5 provides the study limitations and opportunities for further work. Finally, Section 6 concludes by summarizing the main outcomes.

2. Example of contextualization

To illustrate the potential of personalized XR, Fig. 1 showcases a VR-based supermarket experience, where stroke survivors can simulate a typical shopping activity, selecting products based on a pre-existing list. The experience also incorporates the payment process, allowing survivors to complete the full loop of a regular day-to-day activity they will likely engage in after leaving the rehabilitation center. This immersive simulation, created in close collaboration with stroke survivors and

Fig. 1. A stroke survivor, equipped with a VR headset, navigates an immersive supermarket experience designed to simulate a real-life daily activity. The goal is to collect all items from a pre-defined shopping list, encouraging cognitive engagement and task planning. Using hand gestures recognized by the VR hardware, the survivor can naturally interact with products—grasping, lifting, and placing them into the virtual shopping cart — enhancing both motor coordination and functional independence in a controlled rehabilitation setting.
Source: Adapted from: [49].

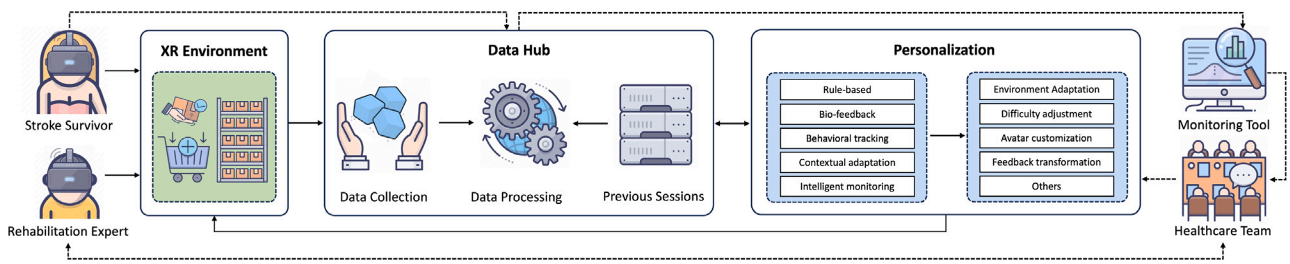

Fig. 2. Conceptual model illustrating a personalized XR-based system for stroke rehabilitation. It consists of: XR Environment—stroke survivors interact with a virtual rehabilitation scenario, while a rehabilitation expert may also be involved; Data Hub—data from user interactions is collected, processed, and compared with previous sessions; Personalization module—Adaptive methods like rule-based adjustments, biofeedback, behavioral tracking, contextual adaptation, or intelligent monitoring may be used to tailor the rehabilitation experience; Monitoring Tool—Healthcare teams can use the data collected and analyze survivors progress to personalize further XR-based interventions.
Source: Adapted from: [48]. Assets from https://iconfinder.com.

healthcare professionals from a renown rehabilitation center, not only provides a realistic environment for rehabilitation but also reinforces important cognitive or motor skills required for everyday tasks [48].

Focusing on the personalization of the VR experience according to the survivor's behavior and reactions during the supermarket activities, several possibilities may occur, as illustrated by the conceptual model of Fig. 2. The experience can adapt to the number and location of products throughout the environment, adjusting the difficulty level based on the survivor's abilities. Additionally, the product list can be modified, starting with easier-to-find items and gradually incorporating more challenging ones that require further exploration of the surrounding space. The payment methods can also be adjusted from virtual money to more sophisticated options like credit cards or digital wallets. The experience can also feature distinct visual aids, such as directional arrows or Non-Player Characters (NPCs) avatars, to help guide the user if they get lost, ensuring that the simulation is both supportive and adaptable.

This approach can ensure that a single VR experience can be adapted to multiple contexts of use, aligning with the specific needs of each stroke survivor. Over time, this dynamic customization may allow for a progressive rehabilitation journey, where survivors move from simpler approaches to more complex tasks [51–54]. By following the same individual over time, the system can provide continuous and evolving support, enhancing their recovery and helping them regain independence in everyday activities. Furthermore, the personalization process can occur at regular intervals, such as every few minutes, or it could be done at the end of the session. This process can be automated by the VR solution or manually adjusted by a healthcare professional through a dedicated interface.

3. Research methodology

This section describes the approach used to conduct the review on personalized XR for stroke rehabilitation (Fig. 3). The process began by defining clear inclusion and exclusion criteria to ensure the relevance of the studies. A comprehensive survey of the SCOPUS database was then conducted, followed by the selection of relevant papers that met the established criteria. Publications that did not align with the focus of the review were excluded. Finally, the selected papers were analyzed to extract key findings regarding the use of personalized XR interventions in stroke rehabilitation.

The goal of this study is to explore methods that, along with XR, can provide more individualized rehabilitation for stroke survivors. To achieve this, we conducted a structured review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [55].

3.1. Paper search

As a starting point for the review, two main research questions were established: *"How can eXtended Reality environments be personalized to adapt to stroke survivors' needs during rehabilitation procedures?"* and *"How does personalization affect a stroke survivor during rehabilitation activities?"*. The purpose of these questions is to identify methods to meet the specific requirements of patients undergoing rehabilitation and the impact they have on recovery progress and engagement.

Our review was designed to be as comprehensive and inclusive as possible. We collected papers from the SCOPUS database due to its broad coverage of journals and conferences. Additionally, based on the

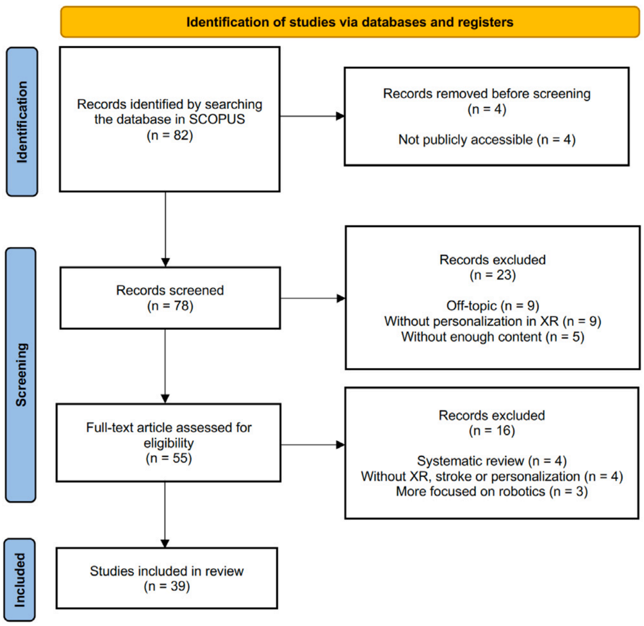

Fig. 3. PRISMA diagram showcasing the approach for the review of personalized XR applications in stroke rehabilitation, resulting in the inclusion of 39 publications, according to the criteria established.

previously defined research questions, it was possible to identify the search terms: “eXtended reality”, “Personalization”, “Rehabilitation”, “Patient” and “Stroke”. For each keyword, we subsequently found other synonyms that allowed us to build the search query. Were used the following search terms:

- (“XR” OR “eXtended reality” OR “Virtual reality” OR “VR” OR “Augmented reality” OR “AR” OR “Mixed reality” OR “MR” OR “Immersive”) AND
- (“Personaliz*” OR “Personalis*” OR “Adapt*” OR “Adjust*” OR “Customiz*” OR “Customis*” OR “Individualiz*” OR “Individualis*”) AND
- (“Rehab*” OR “Recovery” OR “Healing” OR “Improv*” OR “Therapy”) AND
- (“Patient” OR “Survivor” OR “Sick person”) AND
- (“Stroke”)

In addition to the keyword search, we applied the following inclusion criteria to refine the selection of relevant studies:

1. Type of publication: journal article or conference paper;
2. Year of publication: between 2020 and 2024 (inclusive);
3. Language: Written in English;
4. Subject area: engineering and computer science.

We limited our search to journals and conference papers to include only peer-reviewed, high-quality work in our field of research. To ensure the review captured the most current and relevant developments in the field, we limited our search to the past five years, i.e., the period from 2020 to 2024. This time frame reflects the recent surge of interest and progress in applying XR technologies to personalized stroke rehabilitation. Only publications in the English language were considered, as this is the predominant language of academic research. The limitation of the subject area to engineering and computer science has helped to focus the review on specific disciplines directly related to the research topic.

3.2. Analysis process

A total of 82 publications were retrieved (Fig. 3). An initial filtering process was applied to ensure the collected publications aligned with the study's objectives. From an initial analysis, four articles were excluded because they were not publicly accessible and, therefore, could not be analyzed.

For the remaining 78 studies, two screening phases followed. The first phase of screening consisted of analyzing the title and abstract to identify studies relevant to the review objectives. In total, 23 were excluded here. Nine articles were removed for being incorrectly selected during the research process (false positives) and falling outside the scope of the topic. Furthermore, nine articles did not involve personalization with XR. Another five were also excluded, since they lacked sufficient details, i.e., did not clearly describe the intervention or explain how personalization was implemented.

For the remaining 55 articles, the last phase of screening was conducted. To support this process, a table with relevant topics of interest was put together and shared among the research team to summarize key topics and common features among the articles. The table facilitated comparison and discussion, after at least two members analyzed each work, ensuring consistent identification of relevant points.

The reviews of each paper focused on the following attributes: the year of publication and where it was published, as well as the type of publication (conference, journal, or other). The rehabilitation type and specific exercises targeted. Another critical factor was the type of reality used and the interaction mode. The hardware used was also recorded to assess trends in technology adoption. A significant focus was given to personalization, analyzing the types, modes, and frequency of adaptation, along with whether previous session data was leveraged (see Table 1). Studies were also reviewed for user evaluation methods, examining whether they conducted experimental studies, the design used, and the number and characteristics of participants. Details such as the study duration, number of sessions, adaptation periods, and therapist involvement were also recorded. To assess how performance and user experience were measured, we looked at performance metrics, bio-signals, questionnaires, and interviews. Additionally, we noted whether data collected was repurposed for other uses, such as monitoring tools, and what type of data analysis was conducted. Finally, we checked whether studies discussed the potential for telerehabilitation, providing insights into the future scalability of personalized XR-based rehabilitation.

At the end, sixteen more studies were excluded. Specifically, four were systematic reviews, nine lacked a focus on XR, stroke, or personalization, and three dealt mainly with robotics. All in all, by the end of the selection process, 43 articles were eliminated, and 39 were chosen for further analysis (Table 1).

The reduced number of works (39 works analyzed) may be explained by several factors, including the complexity of implementing adaptive systems, limited access to data that can be used for personalization, and the need for interdisciplinary collaboration between technology and healthcare experts. To elaborate, several challenges remain before personalized XR approaches can become commonplace in rehabilitation centers and stroke survivors' homes. Firstly, the integration of advanced personalization methods requires robust data collection and analysis, which can pose technological and privacy concerns. Secondly, designing adaptive systems that respond dynamically to user needs without overwhelming them or increasing system complexity is a delicate balancing act. Finally, ensuring the affordability and accessibility of these technologies is crucial, especially for widespread adoption in resource-limited settings. Also essential is clinical validation of personalized XR interventions, to establish their efficacy and safety. This involves prolonged trials and collaboration between multi-disciplinary teams. Only by addressing these challenges can personalized XR solutions become a viable and impactful tool for stroke rehabilitation.

Table 1
Illustration of some results associated with the 39 results from the scoping review on personalized XR for stroke rehabilitation (2020–2024) [56–94].

ID	Pub.	Year	Rehabilitation Type	Exercise Type	Reality	Personalization Type	Personalization Mode	Personalization Frequency	Operational Mode	Access to previous data	User Evaluation
1	[56]	2021	physical (lower limb)	therapeutic activities	VR	context adaptation	automatic	sync (real-time)	individual	not mentioned	yes (rehab. center + survivor house)
2	[57]	2021	physical (upper limb)	Serious Games	VR	bio-feedback	manual	async (before new session)	individual	not mentioned	no
3	[58]	2023	physical (upper limb)	Serious Games	AR	behavioral tracking	automatic	sync (real-time)	individual	not mentioned	yes (not mentioned where)
4	[59]	2023	physical (upper limb)	Serious Games	VR	rule-based	manual	async (before new session)	individual	not mentioned	no
5	[60]	2021	other	therapeutic activities	VR	context adaptation	manual	async (end of a task)	individual	not mentioned	no
6	[61]	2024	other	Serious Games	VR	behavioral tracking	automatic	sync (real-time)	individual	yes	yes (not mentioned where)
7	[62]	2022	physical (upper limb)	Serious Games	VR	behavioral tracking	manual	sync (real-time)	individual	not mentioned	yes (other)
8	[63]	2024	physical (upper limb)	Daily tasks	VR	behavioral tracking	semi-automatic	async (before new session)	individual	yes	yes (laboratory)
9	[64]	2021	physical (upper limb)	Serious Games	VR	rule-based	automatic	not mentioned	individual	not mentioned	yes (not mentioned where)
10	[65]	2024	physical (upper limb)	Serious Games	VR	bio-feedback	hybrid	hybrid (sync and async)	collaborative (co-located)	no	yes (not mentioned where)
11	[66]	2024	physical (upper limb)	therapeutic activities	VR	bio-feedback	automatic	sync (real-time)	individual	not mentioned	no
12	[67]	2022	physical (upper limb)	Serious Games	VR	rule-based	manual	sync (real-time)	individual	not mentioned	yes (rehab. center)
13	[68]	2022	physical (upper limb)	Serious Games	VR	rule-based	manual	async (occasionally)	individual	not mentioned	yes (survivors house)
14	[69]	2023	physical (upper limb)	Serious Games	VR	rule-based	other	not mentioned	individual	not mentioned	yes (laboratory)
15	[70]	2021	physical (upper limb)	Serious Games	VR	rule-based	manual	async (occasionally)	individual	not mentioned	yes (survivors house)
16	[71]	2023	physical (upper limb)	Serious Games	VR	behavioral tracking	hybrid	hybrid	individual	no	yes (laboratory)
17	[72]	2023	physical (upper limb)	Serious Games	VR	context adaptation	Automatic	async (before new session)	individual	no	yes (laboratory)
18	[73]	2022	cognitive	Serious Games	VR	context adaptation	manual	async (before new session)	individual	yes	yes (laboratory)
19	[74]	2021	physical (upper limb)	Serious Games	VR	context adaptation	hybrid	n/a	hybrid	yes	yes (laboratory)
20	[75]	2023	physical (upper limb)	therapeutic activities	VR	behavioral tracking	automatic	sync (real-time)	individual	yes	yes (laboratory)
21	[76]	2020	physical (upper limb) + cognitive	Serious Games	VR	rule-based	automatic	hybrid (sync and async)	individual	no	yes (rehab. center)
22	[77]	2024	physical (upper limb)	Serious Games	VR	context adaptation	manual	async (before new session)	individual	not mentioned	yes (not mentioned where)
23	[78]	2022	physical (upper limb)	Serious Games	VR	context adaptation	manual	async (occasionally)	individual	no	yes (survivors house)
24	[79]	2021	cognitive	therapeutic activities	VR	rule-based	hybrid	hybrid (sync and async)	individual	not mentioned	yes (not mentioned where)
25	[80]	2022	physical (upper limb)	Daily tasks	VR	bio-feedback	manual	async (before new session)	individual	yes	yes (laboratory)
26	[81]	2020	physical (lower limb)	Daily tasks	VR	bio-feedback	semi-automatic	sync (real-time)	individual	yes	yes (laboratory)
27	[82]	2020	physical (upper limb)	Serious Games	VR	rule-based	semi-automatic	sync (real-time)	individual	not mentioned	yes (laboratory)
28	[83]	2024	physical (lower limb)	Daily tasks	AR	bio-feedback	automatic	sync (after a period)	individual	not mentioned	yes (laboratory)
29	[84]	2023	physical (upper limb)	Serious Games	VR	bio-feedback	hybrid	hybrid (sync and async)	individual	no	yes (other)
30	[85]	2021	other	Serious Games	VR	behavioral tracking	automatic	sync (real-time)	individual	no	yes (other)
31	[86]	2024	cognitive	Serious Games	hybrid	behavioral tracking	automatic	sync (real-time)	individual	yes	yes (other)
32	[87]	2024	physical (upper limb)	Serious Games	VR	behavioral tracking	automatic	sync (real-time)	individual	yes	yes (survivors house)
33	[88]	2021	physical (upper limb)	therapeutic activities	VR	behavioral tracking	automatic	sync (real-time)	individual	yes	no
34	[89]	2020	physical (upper limb)	Serious Games	VR	behavioral tracking	automatic	sync (real-time)	individual	yes	yes (laboratory)
35	[90]	2022	physical	therapeutic activities	VR	bio-feedback	automatic	sync (real-time)	individual	not mentioned	yes (laboratory)
36	[91]	2023	physical (upper limb)	therapeutic activities	VR	context adaptation	Automatic	not mentioned	individual	not mentioned	yes (not mentioned where)
37	[92]	2020	physical (upper limb)	Serious Games	VR	rule-based	automatic	sync (real-time)	individual	yes	yes (at home)
38	[93]	2022	physical	therapeutic activities	VR	bio-feedback	automatic	sync (real-time)	multi-user	not mentioned	no
39	[94]	2024	physical	Serious Games	AR	behavioral tracking	manual	sync (real-time)	not mentioned	not mentioned	yes (not mentioned where)

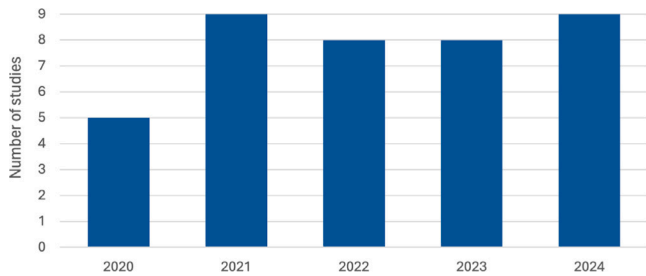

Fig. 4. Distribution of the number of publications on personalized XR for stroke rehabilitation from 2020 to 2024, showing an increasing trend in research activity, with further growth from 2021.

4. Results and discussion

This section describes the key findings from the scoping review of personalized XR applications in stroke rehabilitation, highlighting the trends, advancements, and challenges identified across the selected studies. It is explored the evolution of the research over the five years, the publication types, and focus areas. The rehabilitation approaches and exercise designs are analyzed, as well as the technological components adopted, such as the type of XR, mode of interaction, and hardware. Regarding the personalization strategies, it covers how the adaptation is implemented, for whom it is intended, and how it aligns with the user's needs. Furthermore, the section discusses how user evaluation is conducted, including experimental setups and participant involvement, reviewing also the methods used for data collection and outcome evaluation. Throughout the section, as the results are explored, several conclusions are also drawn, revealing important trends, innovations, and persistent challenges in the development and evaluation of personalized XR solutions for stroke rehabilitation.

4.1. Publications through the years

The distribution of publications over the years indicates a growing interest in personalized XR experiences for stroke rehabilitation, particularly in recent years. While there are some publications from 2020 and 2021, the number of studies appears to increase steadily from 2022 onward, with a significant concentration of publications in 2023 and 2024 (as illustrated in Fig. 4). This trend suggests that research in this field is gaining momentum, likely driven by advancements in XR technologies, intelligence algorithms, or data-driven personalization techniques, among other possibilities. The rise in publications also reflects an increasing recognition of the limitations of traditional rehabilitation methods and the potential of XR-based personalization to enhance recovery outcomes. However, despite this growth, the field remains relatively young, and there is still much work to be done in terms of standardization, large-scale validation, and real-world implementation (as will be illustrated in the next sub-section). This pattern underscores the importance of continued research efforts to refine and expand the use of personalized XR solutions in stroke rehabilitation.

4.2. Publication type

The analysis of the publication type reveals three categories. The majority of publications, 29 out of 39 (74.4%), fall under the system + study category, indicating a focus on both the system's development and the associated study. This suggests that most works combine practical system development with an evaluation. A smaller portion, six out of 39 (15.4%), focus solely on the system, highlighting research centered on the technical or developmental aspects of the system without a connected study. Finally, four works (10.2%) focus exclusively on the study, emphasizing research findings related to stroke rehabilitation without a specific focus on the system itself. This distribution shows that while the combination of system and study is most common, there is still a significant number of works focusing on either the system or the study independently.

4.3. Rehabilitation type

Overall, our analysis suggests that while significant progress has been made in using XR for upper limb rehabilitation, further efforts are required to ensure a more comprehensive and personalized approach to stroke recovery.

4.3.1. Physical rehabilitation

The distribution of research topics within personalized XR for rehabilitation type reveals a strong emphasis on physical rehabilitation, particularly targeting the upper limb. A significant portion of the studies, 26 out of 39 (66.7%), focuses on improving motor function in the arms, hands, and shoulders, reflecting the high prevalence of upper limb impairments following a stroke. While lower limb rehabilitation is also explored, three out of 39 (7.7%), it appears less frequently, suggesting that more research may be needed to address gait and mobility recovery through XR-based interventions. This may also be explained by the fact that upper limb recognition technologies are particularly more developed than those for the lower limb, making it easier to track and create rehabilitation exercises for the arms and hands.

Hand-tracking sensors, and controllers have advanced significantly, enabling precise adaptation of upper limb movements. In contrast, lower limb rehabilitation often requires more complex full-body motion tracking, which are still evolving. As a result, the development of personalized XR experiences may face additional technical challenges, indicating a need for further innovation in sensor technologies, biomechanics modeling, and real-time feedback systems to provide an equally effective solution for lower limb recovery.

4.3.2. Cognitive rehabilitation

Beyond physical rehabilitation, there are also studies on cognitive rehabilitation, three out of 39 (7.7%), covering aspects such as visuospatial neglect and general cognitive training. These efforts highlight the potential of XR to engage stroke survivors in interactive exercises that stimulate cognitive recovery alongside motor improvements. Additionally, only one publication (2.3%) explored multimodal approaches, combining physical and cognitive rehabilitation, recognizing the interconnected nature of these impairments in stroke survivors.

4.3.3. Others

A smaller but notable portion of the studies focuses on other rehabilitation needs, including balance training, speech therapy, or others, six out of 39 (15.4%), emphasizing the versatility of XR in addressing different challenges faced by stroke survivors. However, given the relatively lower number of studies in these areas, there is an opportunity for future research to expand on underrepresented aspects of stroke rehabilitation, such as speech, balance, and holistic multi-domain interventions [28,36].

4.4. Rehabilitation exercises

The reviewed studies employed a variety of rehabilitation exercises, which can be broadly categorized into three main approaches based on their design and therapeutic goals: serious games, simulations of real-life therapeutic activities, and simulations of daily tasks.

4.4.1. Serious games

A significant portion of the rehabilitation exercises, 26 out of 39 (67%), uses serious games as a primary intervention method to improve both cognitive and physical functions. These games, such as basketball training (shooting), table tennis, and Tetris-like games, are designed to improve both cognitive and physical functions, which can make rehabilitation more engaging and enjoyable for stroke survivors, potentially leading to better adherence to the therapeutic process.

4.4.2. Simulation of real-life therapeutic activities

Another prominent approach, in nine out of 39 (23%), includes task-oriented training through exergames. These exercises simulated real-life therapeutic activities, such as palmar grasping or Mirror Therapy, being focused on improving physical functions like dexterity, balance, and motor coordination. Additionally, exercises such as identifying shapes have been shown to improve fine motor skills and executive functions like spatial orientation and memory. This category blends physical and cognitive training, offering a holistic rehabilitation strategy.

4.4.3. Simulation of daily tasks

Moreover, four works (10%) involved simulations of everyday tasks, such as street walking and eating tasks like steak-cutting. These simulations are designed to help patients regain the motor skills necessary for real-life activities, enhancing their independence in daily living. Activities like walking simulation can improve gait, balance, and mobility, while task simulations (like cutting steak or performing household tasks) help rebuild motor control, dexterity, and executive function in a controlled, yet realistic, environment.

4.5. Digital reality

The analysis of the XR technologies reveals a strong preference for VR as the primary modality. Out of the 39 publications analyzed, an overwhelming 35 studies (84.6%) focused on VR-based rehabilitation, demonstrating its dominant role in this field. This preference can be attributed to VR's ability to create fully immersive and controlled environments, allowing for personalized and engaging rehabilitation experiences tailored to each stroke survivors' needs.

In contrast, AR was explored in only three studies (7.7%), suggesting that its potential for stroke rehabilitation remains underdeveloped compared to VR. AR could offer advantages in blending virtual elements with real-world interactions, potentially supporting rehabilitation tasks that require engagement with physical objects or environments. However, the lower adoption rate might be linked to technical challenges in precise motion tracking, interaction accuracy, and seamless integration of AR elements into rehabilitation exercises.

Furthermore, due to AR's nature, not all stroke survivors may fully perceive and comprehend virtual content superimposed on the real world. This may force researchers and healthcare professionals to be less inclined to invest in AR-based solutions, given the potential usability challenges for certain patients.

Additionally, hybrid approaches that combine multiple XR technologies appeared in one study (2.6%), suggesting a growing interest in integrating different modalities to enhance rehabilitation effectiveness.

A few studies, in two out of 39 (5.1%), specifically examined non-immersive VR setups, such as desktop-based VR exergames, which could provide a more accessible alternative for stroke survivors who may struggle with fully immersive systems. One study also combined VR with Electroencephalogram (EEG) feedback, showcasing efforts to integrate neurophysiological data into rehabilitation.

4.6. Interaction mode

The selection of the interaction mode plays a critical role in the effectiveness of stroke rehabilitation, ensuring accessibility, usability, and engagement. The modes used across the reviewed studies varied significantly, reflecting the diverse approaches to engage stroke survivors in XR-based rehabilitation.

4.6.1. Hand tracking

One widely used interaction mode is hand tracking, which appeared in 16 of the 39 studies analyzed (41%). This type of interaction relies on specialized cameras, such as depth and RGB cameras, used to capture hand movements. The images can track finger joint positions and palm movements, translating them into interactions in the virtual environment in real time. In the same direction, head tracking was also identified in one of the articles analyzed (2.6%).

4.6.2. Controllers

Another common interaction mode are controllers. These devices, such as the HTC Wand Controllers, PlayStation Move controllers, Valve Index, etc., provide both positional and rotational tracking, multiple buttons to interact with virtual objects, and some level of haptic feedback. By improving the sense of agency and presence, controllers can positively impact the immersiveness of the experience. In the present analysis, 10 of 39 articles (25.6%) incorporated the use of controllers as an interaction method. It should be highlighted that, while controllers offer precise input, their reliance on fine motor skills may exclude individuals with severe upper limb limitations.

4.6.3. Gait

Gait tracking was described in 2 out of the 39 studies analyzed (5.1%). This interaction mode enables the assessment of walking patterns and allows for continuous monitoring of a patient's gait throughout different stages of rehabilitation. By providing real-time data, gait tracking supports personalized therapy and progress evaluation.

4.6.4. Biosignals

Regarding the collection of biological data, Brain–Computer Interface (BCI) controllers were used in two of the studies analyzed (5.1%). This technology enables users to control virtual environments using brain activity by capturing electrical brain signals and translating them into commands within the XR application. In addition, gaze and eye-tracking is applied in one study (2.6%), allowing users to navigate and control the virtual environment through eye movements.

4.6.5. Others

The remaining studies (18%) explored various other interaction modes, including virtual paddles, the WIN-POSTURO platform, EMG-to-force mapping estimation, and camera-based tracking of a billiards stick. These varied interaction methods highlight the field's effort to tailor engagement mechanisms to different rehabilitation needs, ensuring accessibility and effectiveness across diverse populations.

4.7. Personalization type

Focusing on the type of personalization for XR-based stroke rehabilitation, taking into account the types aforementioned [48], out of 39 responses, the most frequently mentioned personalization types are bio-feedback, behavioral tracking, and rule-based systems, which collectively represent over 56% of the data (as illustrated in Fig. 5).

To elaborate, behavioral tracking is the most common approach to personalization, appearing in 12 works (30.8%), suggesting that the systems used tracked the user's movements, actions, or behaviors to personalize the XR environment during the rehabilitation process. Rule-based approaches were integrated by 10 works (25.6%) involving pre-programmed rules that control how the XR environment adjusts based on specific criteria or conditions. Bio-feedback appeared in nine works (23%), being typically used to collect users' real-time physiological data (such as heart rate) to inform them of their performance and help adjust their behavior or movements during rehabilitation. Moreover, eight works explored context adaptation (21%), adjusting the XR environment based on contextual factors such as the user's mood, fatigue levels, or prior rehabilitation session data. These findings highlight the diversity of personalization strategies employed in

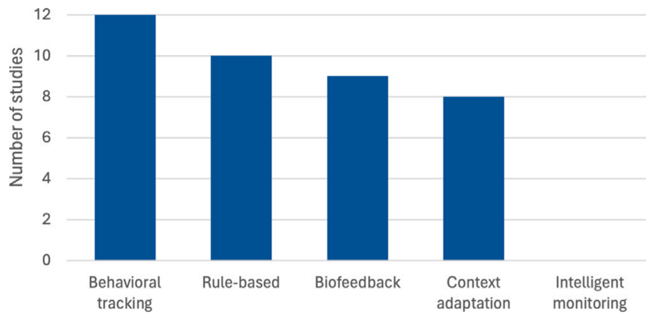

Fig. 5. Distribution of publications across different personalization methods, highlighting Behavioral tracking as the most studied approach, followed by Rule-based and Biofeedback methods.

XR-based stroke rehabilitation. While we initially expected rule-based approaches to be the most widely adopted—given their straightforward implementation and ease of testing, the results reveal a more evenly distributed adoption of various personalization methods. This suggests that researchers are exploring multiple strategies rather than relying solely on predefined rules, possibly due to the potential benefits of more dynamic and responsive personalization methods. Notably, our review did not find any results on personalization using intelligent monitoring. This may be attributed to the fact that implementing such systems may require advanced Machine Learning (ML) and Artificial Intelligence (AI) models, large datasets, and real-time processing capabilities, which can be challenging to develop and integrate into XR-based rehabilitation, particularly given the financial limitations of rehabilitation centers as well as involving privacy concerns. Additionally, many studies may still be in preliminary stages, focusing on simpler personalization techniques before advancing to more complex approaches.

4.7.1. Mode of personalization

Regarding the personalization mode, out of 39, 18 articles (46.2%) use an automatic mode, which suggests that a significant portion of XR systems rely on automated adjustments to customize the rehabilitation process for individual patients. In comparison, manual personalization is employed in 11 works (28.2%), indicating that a smaller proportion of systems rely on manual input, either from therapists or patients themselves, to adjust the rehabilitation exercises. This could involve therapists manually adjusting settings or overseeing the process based on observations or feedback from the patient. There are also semi-automatic/hybrid modes used in eight works (20.5%), which combine elements of both automatic and manual personalization. These systems may allow some level of automation but still require human oversight or input to ensure the exercises are appropriately tailored to the individual's needs. Besides, the remaining works (5.1%) were not clear regarding the mode of personalization.

4.7.2. Synchronization type

Analyzing the synchronization type during the rehabilitation process reveals a notable preference for synchronous methods. Out of the 39 works, 19 (48.7%) employ a synchronous mode of personalization, especially in real-time settings. This suggests that a significant majority of XR-based rehabilitation systems prioritize immediate adaptation or feedback, which can be crucial for maintaining stroke survivors engagement and optimizing therapeutic outcomes.

Among these synchronous methods, real-time feedback or adjustments were the most common. This shows a strong trend towards systems that adjust exercises or provide feedback dynamically during the rehabilitation session itself. This real-time engagement is beneficial for survivors, as it offers instant corrections and allows them to track their progress continuously.

In contrast, asynchronous personalization appears in 11 articles (28.2%), where the system makes adjustments based on previously collected data. Some of these systems analyze data before a new rehabilitation session (six systems) or immediately at the end of a task (two of them). There are also systems that adjust occasionally (three articles) based on accumulated data or intermittent observations, suggesting that in these cases, feedback is less immediate but may still contribute to long-term rehabilitation planning.

Hybrid modes, combining synchronous and asynchronous methods, are used in six works (15.4%). This combination allows for flexibility, as it offers both real-time adjustments and periodic data reviews, providing a balanced approach to personalization. Lastly, three works (7.7%) did not provide sufficient information, either because no personalization frequency was specified or the method was not clearly described.

4.7.3. Intended audience

The majority of the studies analyzed focused on individual rehabilitation, 36 out of 39 (92.3%), reinforcing the idea that most XR-based stroke rehabilitation solutions are designed for personalized, self-paced exercises. This aligns with the need for tailored rehabilitation programs that adapt to each survivor's specific progress and limitations.

However, two studies (5.1%) explored collaborative approaches, including co-located multi-user experiences. These approaches could introduce valuable elements such as social interaction, peer support, and shared motivation, which are often lacking in traditional rehabilitation. Social engagement has been shown to improve motivation, adherence, and overall recovery outcomes, suggesting that more research into collaborative XR rehabilitation is warranted.

In addition, one study (2.6%) did not mention the intended audience. As such, as XR rehabilitation systems continue to evolve, future work should explore how multi-user and social rehabilitation approaches can complement individual exercises, potentially improving engagement and long-term adherence.

4.7.4. Support for accessing data from previous sessions

From the results, we can infer that access data from previous sessions was limited in most systems. Specifically, 27 out of 39 papers (69.2%) did not mention any form of access to previous session data, while only 12 studies (30.8%) had such access features, which were illustrated through simple analysis. This suggests that relatively few systems incorporate mechanisms to retrieve and analyze data from previous rehabilitation sessions.

There are several reasons why this could be the case. Implementing data access features requires a multidisciplinarity approach, combining expertise in areas like interaction design, data management, data visualization, and rehabilitation therapy, among others. For many research teams, assembling such a diverse set of skills can be challenging. They might lack the resources or personnel needed to integrate these advanced functionalities into their systems, making it more difficult to achieve the desired results.

Only more advanced works in the field tend to delve into these types of features, suggesting that adding support for data access may be a step that comes later in the development cycle. However, having access to previous session data could be highly relevant for improving the effectiveness of XR-based rehabilitation systems. It allows for personalized adjustments based on a patient's progress, leading to more tailored and adaptive rehabilitation programs. This type of feature can also enhance motivation and engagement, as patients and therapists can track improvements and setbacks over time.

4.7.5. Potential for telerehabilitation

Out of the 39 works, 11 (28.2%) clearly stated a strong potential for telerehabilitation in the proposed systems. This suggests that they either include the infrastructure or capabilities to be used remotely or could be adapted for supporting remote therapy, either for home use or through remote monitoring by therapists. Some works have hinted at telerehabilitation indirectly. For example, there are mentions of systems that provide exercises to be done at home with the ability to connect to health professionals online (3 instances). These works point to a potential for remote use, though they may not have been explicitly categorized under telerehabilitation.

In total, seven works (18%) explicitly mention no potential regarding telerehabilitation. This could be due to limitations in system design, a lack of remote access features, or a primary focus on in-person rehabilitation. These results emphasize that a significant portion of the systems reviewed either do not have the infrastructure for remote care or have not integrated it into their design, highlighting an opportunity for widespread implementation of personalized XR-based telerehabilitation systems.

Plus, there are 21 works (53.8%) where telerehabilitation potential is not mentioned. This may indicate that the study or the system's features did not specifically address the possibility of remote therapy, leaving the potential open but unspecified.

4.8. Hardware

The analysis of hardware used across studies reveals a strong preference for immersive VR head-mounted displays (HMDs), with 22 out of 39 studies (56.4%) employing devices such as the HTC Vive, Oculus Quest 2, and Pico Neo. This suggests a trend towards fully immersive environments for stroke rehabilitation. Furthermore, some studies (four out of 39–10.3%) employed non-immersive or desktop-based VR, showing that alternative approaches are still considered viable, particularly when accessibility or hardware constraints are factors. Additionally, six out of 39 studies (15.4%) utilized Kinect-based motion tracking, emphasizing the role of non-wearable sensor-based solutions. Some studies explored customized or hybrid setups (six out of 39–15.4%), such as haptic gloves, exoskeletons, projection systems, and Leap Motion controllers, demonstrating efforts to refine interaction and motion tracking. Notably, some of these studies integrated biosensors, such as EMG and EEG, highlighting the need for additional research on physiological feedback in rehabilitation. With even less focus, only one study (2.5%) integrated an AR headset, specifically the Microsoft HoloLens 2, highlighting that AR is still in its early stages in rehabilitation. However, with the emergence of more accessible devices like the Oculus Quest 3, this trend may shift as such devices become more affordable and widely available, potentially leading to an increased adoption of AR in rehabilitation settings in the future. All in all, the variety of hardware choices underscores the field's ongoing experimentation with different levels of immersion for stroke survivors.

4.9. User evaluation

User evaluations were conducted in a majority of the studies, with 33 out of 39 (84.6%) explicitly mentioning an evaluation process. And so, as 6 of the 39 (15.38%) did not report any evaluations with users were therefore not considered for the data reported in this subsection. The following analysis was conducted on the remaining 33 articles. Among these 33, 11 studies (37.9%) took place in a laboratory setting, which is a controlled environment allowing for precise monitoring and assessment. Plus, three studies (10.3%) were conducted at a rehabilitation center, where real-world clinical conditions were considered. Moreover, four studies (13.8%) involved evaluations at a stroke survivors' home, providing insight into home-based rehabilitation scenarios. A smaller portion, four studies (13.8%), took place in other locations, which could include mixed settings or alternative rehabilitation spaces. Additionally, seven studies (24.1%) mentioned evaluations but did not specify the location, making it unclear whether they were conducted in laboratory, clinical, or home settings.

However, four studies out of 33 (12.1%) only focused on system development or theoretical assessments rather than hands-on testing. All in all, the overall distribution shows a strong focus on real-world applicability, with a significant number of studies prioritizing controlled environments, while some also explore more natural rehabilitation settings.

4.9.1. Experimental design

The experimental design choices among studies reflect different methodological approaches to evaluating XR-based stroke rehabilitation. A majority of studies adopt a within-subjects design, 17 out of 33 (51.5%), where the same participants experience multiple conditions. This approach allows researchers to directly compare different rehabilitation methods while controlling for individual variability.

A smaller portion of studies employed a between-subjects design, six out of 33 (18.2%), where different participants tested separate conditions, reducing potential learning effects but requiring larger sample sizes to ensure statistical significance.

Notably, several studies do not specify their experimental design, 10 out of 33 (30.3%), which may limit replicability and clarity in interpreting results. Future research should strive for clearer reporting of experimental design choices.

4.9.2. Participants

The analysis of participant types in the studies reveals a diverse range of groups involved. Stroke individuals are the most common participant group, appearing in 15 out of 33 studies (45.5%), confirming that nearly half of the research directly targets stroke survivors. Healthy individuals, including students and elderly participants, are featured in seven out of 33 studies (21.2%), likely serving as control groups or early-stage testers for the systems. A combination of stroke and healthy individuals is present in three out of 33 studies (9.1%), suggesting comparative studies or mixed-group evaluations. Plus, healthcare professionals are included in three out of 33 studies (9.1%), indicating research focused on the perspectives of therapists, or medical staff in using XR-based rehabilitation systems. In five out of 33 cases (15.2%), participant details are not specified, suggesting either conceptual studies or early-stage system development without direct user testing.

All things considered, while stroke survivors remain the primary focus, the involvement of healthy individuals and healthcare professionals highlights the broader scope of research in XR-based rehabilitation. Compared to other areas of XR research [95], where most studies rely on students as the main samples, this demonstrates a commitment to a more ecological approach for the field of personalized XR rehabilitation. The inclusion of diverse participant groups, particularly stroke survivors and healthcare professionals, illustrates an effort to test these systems in real-world clinical settings, ensuring that development aligns with the needs of target users rather than just theoretical or technical feasibility. This focus on personalization strengthens the potential for XR technologies to deliver meaningful and effective rehabilitation outcomes.

The number of participants in the analyzed works varies widely, reflecting differences in study scope, research objectives, and system maturity.

Small-scale studies with 1–5 participants are common, appearing in 10 out of 33 cases (30.3%), indicating the frequent use of early-stage or pilot studies to test feasibility. Slightly larger studies with 5–10 participants are present in three studies (9.1%), suggesting controlled but still limited testing. A notable portion of studies, seven out of 39 (21.2%), falls within the 10–15 participant range, showing a trend towards mid-sized evaluations that provide more meaningful insights while maintaining manageable study sizes. The 15–20 participant range appears in five studies (15.2%), highlighting research that balances sample size with logistical constraints. Studies with 20–25 participants are less common, appearing in two cases only (6.1%), while larger studies with 30 or more participants occur in five cases (15.2%), typically representing more advanced research phases or broader evaluations. There is also one case (3%) where the number of participants is not specified, which may indicate conceptual work or studies focused on system development rather than empirical testing. Overall, the distribution suggests that while small-scale studies dominate, there is a considerable number of mid-sized studies, with larger participant groups found primarily in more developed research.

The analysis of previous experience with XR among participants reveals that a majority of studies do not report this information, with 20 out of 33 studies (60.6%) not mentioning prior exposure to XR technologies. This suggests that many studies either did not consider previous experience as a relevant factor or did not collect this data explicitly.

Among the studies that do report participant experience, eight (24.2%) indicate that participants had little to no prior exposure to XR. In contrast, five studies (15.2%) mention some level of prior experience, with a few specifying categories such as VR or video game experience. The presence or absence of XR experience can impact how participants interact with rehabilitation systems, influencing usability, learning curves, and engagement. Given that many stroke survivors and older adults may have limited exposure to XR, ensuring user-friendly interfaces and gradual adaptation strategies remains crucial for effective implementation, which will be put into perspective in the next section.

4.9.3. Adaptation period

The presence of an adaptation period during the user studies varies across the analyzed studies, reflecting different approaches to familiarizing users with personalized XR-based rehabilitation systems.

Results show that 19 out of 33 studies (57.6%) explicitly mention an adaptation period, indicating a structured effort to help participants, particularly stroke survivors, familiarize themselves with the technology before full engagement in rehabilitation exercises.

Contrarily, five studies (15.2%) explicitly state that no adaptation period was provided. This could suggest a focus on intuitive system design or an assumption that users can engage with the system without prior familiarization. However, the absence of adaptation may also present challenges, particularly for individuals with limited prior experience with XR technologies.

Additionally, in nine studies (27.3%), an adaptation was not mentioned, leaving uncertainty about whether users received any preparatory support.

4.9.4. Number of sessions

The number of sessions varied across the studies, reflecting different experimental designs and rehabilitation protocols.

In 10 out of 33 studies (30.3%), there was only a single session, indicating that these works primarily focused on feasibility testing, initial evaluations, or short-term assessments rather than longitudinal rehabilitation.

Studies that included two to five sessions accounted for four cases (12.1%), suggesting a slightly extended engagement but still relatively short-term exposure to the XR rehabilitation systems. A moderate number of studies, nine in total (27.3%), involved between five and 10 sessions, allowing for a more structured rehabilitation process and the ability to assess user adaptation and short-term progress. A smaller subset, three studies (9.1%), reported more than 10 sessions, with one study reaching 40 sessions, indicating a stronger emphasis on long-term rehabilitation and consistent system use over time.

Last, seven studies (21.2%) did not specify the number of sessions, leaving uncertainty regarding the extent of user engagement.

The overall distribution highlights that while many studies remain short-term, there is some effort to explore prolonged interventions, which could provide deeper insights into personalized XR-based system effectiveness and long-term usage.

4.9.5. Study duration

In terms of the duration of the study, the length of the experimental sessions can vary significantly, depending on the objectives of the research and the nature of the rehabilitation system.

In the articles analyzed, some of them conducted single-session experiments, while others extended the sessions over several weeks or months. In the single-session studies, 14 out of 33 (42.4%), the duration varied from 1–10, 10–20, 20–30, 30–60, or over 60 min. On the other hand, long-term sessions account for seven out of the 33 works analyzed (21.2%). These include, for example, six sessions of 15 min, four sessions of 90 s, a 12-week study, two months of study with a total of 33 h, and others. The variability in session length suggests differing approaches to balancing rehabilitation intensity with participant fatigue and engagement.

A considerable number of studies, 12 out of 33 (36.4%), do not mention session duration, highlighting a potential gap in reporting that may hinder reproducibility and comparison across studies. Future research could benefit from more standardized reporting on session duration and its impact on rehabilitation outcomes, ensuring better comparability and guiding best practices for personalized XR-based stroke rehabilitation.

4.9.6. Involvement of healthcare professionals

The involvement of therapists in user studies varies significantly across the analyzed research, reflecting different approaches to integrating professional expertise into XR-based rehabilitation.

In 12 out of 33 studies (36.4%), therapists played an active role, either by supervising sessions, selecting participants, adjusting parameters, or providing direct guidance on rehabilitation exercises. This highlights a subset of studies where therapist involvement is central, ensuring clinical oversight and alignment with rehabilitation goals.

In nine studies (27.3%), the therapists were not involved, indicating a research focus on self-guided rehabilitation or systems designed for independent use. While these approaches may aim to enhance accessibility and scalability, they may also lack immediate expert feedback, which could impact adaptation to the individual needs of stroke survivors.

Besides, therapists also contributed in other capacities in five studies (15.2%), including participation in prototype creation, and evaluating solutions before they were tested by stroke survivors. Additionally, two studies (6.1%) mention therapist involvement in data analysis. Finally, for five studies (15.2%), therapist involvement is not mentioned, leaving uncertainty about the extent of professional supervision.

4.10. Data collection

Next, further details are provided regarding the different methods used to assess XR-based stroke rehabilitation. The following subsections will discuss the use of performance metrics, questionnaires for gathering user feedback, and the role of bio-signals in monitoring physiological responses. Additionally, insights from interviews, details regarding if the data collected was used for alternative purposes, and the types of data analysis conducted.

4.10.1. Performance metrics

From the list, the following trends can be observed. Metrics related to performance, such as game score, and accuracy appear in seven articles, which accounts for 21.2% of the total analyzed works. These metrics are likely linked to task completion or in-game performance, highlighting the importance of tracking stroke survivors interaction during activities. Functional performance metrics like task completion time, number of errors, and success rate are also mentioned six times (18.2%).

In addition, range of motion, arm angle, movement measurements, finger flexion, and gait speed, are mentioned in 16 works, representing 48.5%. These are important for evaluating motor function, especially in rehabilitation contexts like stroke recovery or physical therapy. There are also one occurrences where performance metrics are not mentioned (about 3%), showing that a majority of metrics are being considered or implemented in the context of the activities being analyzed.

The remaining three articles do not specify the performance metrics (9.1%).

As expected, this analysis demonstrates a strong focus on movement-related and functional performance metrics, with a significant emphasis on assessing motor function and task completion in rehabilitation activities.

4.10.2. Usage of bio-signals

It is also possible to identify a few specific bio-signals that appear multiple times. For instance, EMG, is mentioned in three articles, which represents about 7.7% of the total entries. Likewise, EEG is also only mentioned three times, which is another 7.7%. Moreover, HR and ECG are also referenced in three works (again, 7.7%). The rest of the works do not mention using bio-signals, which accounts for a larger portion of the list. This indicates that while the listed bio-signals like EMG, HR, and EEG are important in specific contexts, they make up a relatively small percentage of the total (around 7.7%).

The remaining articles, 30 out of 39 (76.9%), did not mention any use of bio-signals. The relatively low mention of bio-signals could be due to the challenges of collecting them, especially for stroke survivors. These individuals may already be dealing with physical and emotional strain [3,96,97], making the use of additional invasive sensors and wires uncomfortable. The focus might shift towards more user-friendly, non-invasive technologies (e.g., radar-based data collection) to ensure a comfortable experience, particularly in settings like VR, where simplicity and ease of use are key.

4.10.3. Questionnaires and interviews

The majority of works included some form of questionnaire, with a significant preference for personalized ones. In 16 of the 33 analyzed articles (48.5%), the questionnaires were tailored to individual needs or specific aspects of the study. In contrast, existing questionnaires were referenced eight times (24.2%), such as the Falls Efficacy Scale-International (FES-I), Postural Assessment Scale (PASS), Intrinsic motivation inventory (IMI), System Usability Scale (SUS), User experience questionnaire (UEQ), Cybersickness questionnaire, Montreal cognitive assessment, or Fugl-Meyer Assessment. A hybrid approach, i.e., a combination of personalized and existing questionnaires, appeared in five articles, representing 15.2%. Moreover, out of the 33 works, four (or 12.1%) did not perform any questionnaire.

As for interviews, out of the 33 studies, four included interviews as part of their methodology, representing 12.1% of the total. Meanwhile, 23 studies did not use interviews (accounting for 69.7%). The remaining six studies did not mention whether interviews were conducted (making up 18.2%).

4.10.4. Usage of data collected for other purposes

Among the analyzed studies, 13 out of 33 (39.4%) utilized collected data for additional purposes, such as monitoring or further analysis. In contrast, seven studies (roughly 21.2%) explicitly stated that data was not used beyond the immediate rehabilitation session. A significant portion, 13 out of 33 (about 39.4%), did not provide any mention of whether the collected data was used for further applications or not. These findings indicate that while some studies explore the potential of collected data for monitoring and adaptation, many do not explicitly address its further use, underscoring an opportunity to enhance the role of data in supporting long-term rehabilitation strategies.

4.10.5. Type of data analysis conducted

The type of data analysis conducted varied significantly across studies, reflecting different levels of methodological rigor. A considerable number of works relied on simple analysis, 17 out of 33 (51.5%), which often included basic qualitative observations without extensive validation. Statistical analysis was performed in 14 out of 33 studies (42.4%), indicating a stronger emphasis on data-driven conclusions, often using inferential statistics to assess the effectiveness of interventions. Additionally, a few papers (6.1%) did not include any analysis, suggesting early-stage work. This distribution highlights the need for more rigorous and standardized analytical approaches to strengthen the evidence base for personalized XR.

5. Reflection and limitations

This section reflects on the results obtained, describes potential areas for further research and identifies the limitations of the scoping review, promoting transparency.

5.1. Summary of main insights

To synthesize the findings from our review, the field of personalized XR for stroke rehabilitation is steadily evolving, with most publications emerging after 2021, indicating growing research interest and technological advancement. The majority of studies focus on upper limb physical rehabilitation, often through VR-based interventions, which dominate the landscape. Serious games are the most common type of exercise design, followed by simulations of therapeutic activities and daily tasks. In terms of personalization, rule-based systems, behavioral tracking, and bio-feedback were the most frequently used strategies. These were primarily implemented through automatic or synchronous adaptation mechanisms. Notably, 92.3% of the systems targeted individual rehabilitation, with only limited exploration of collaborative or multi-user settings, indicating a strong focus on tailoring interventions to the needs of individual stroke survivors.

As for user evaluation, the sample sizes were generally small. On average, most studies involved short-term engagement: about 30% conducted only a single session, and only 9.1% reported more than 10 sessions. Session durations varied widely, but 42.4% of the works reported experiments lasting between 10 and 60 min. These numbers reflect the exploratory nature of much of the research and suggest a need for more longitudinal, large-scale evaluations. While some systems showed potential for telerehabilitation, this was not addressed in over half the studies, and support for accessing data from previous sessions important for tracking progress and adapting over time was present in only a small part of the cases. Collectively, these findings highlight both the promise and current limitations of personalized XR systems for stroke rehabilitation, pointing to the need for more robust validation, scalable deployment, and user-centered design.

5.2. Taxonomy proposal

The scoping review enabled a comprehensive analysis of the current landscape surrounding personalized XR applications for stroke rehabilitation. Through this process, we were able to understand how personalization has been approached by the research community, identifying patterns, methods, and gaps in implementation across various studies. This analysis also allowed us to systematize the accumulated knowledge in the form of a taxonomy proposal (as illustrated in Fig. 6). The taxonomy serves not only as a synthesis of the findings but also as a structured framework to guide future developments in the field.

This taxonomy highlights the critical dimensions and categories derived directly from our analysis, offering a comprehensive and focused overview. It aims to capture the essential aspects that shape how personalization in XR-based rehabilitation is conceptualized, implemented, and experienced by stroke survivors. The dimensions and

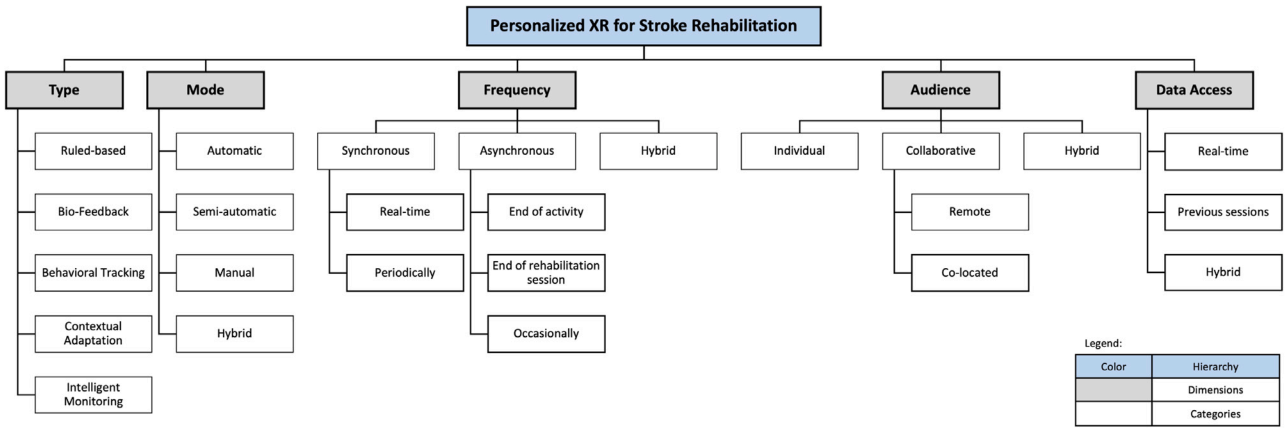

Fig. 6. Taxonomy proposal according to the results analyzed, including the different dimensions and categories for personalization of XR experiences associated with stroke rehabilitation.
Source: Inspired by the work of [98].

categories were selected to reflect the findings of the review. Specifically, the main dimensions: **personalization type, personalization mode, synchronization mode, intended audience, and support for accessing data from previous sessions** align directly with the key subtopics covered in Section 4.7. These aspects were identified as core to the personalization process itself. In contrast, other topics such as digital reality type, interaction mode, hardware, or user evaluation, while important, were not considered from the taxonomy as they are either addressed in existing taxonomies or are peripheral to the personalization mechanisms that form the core focus of this work.

Each category within the taxonomy was derived from the complete set of possibilities reported in the analyzed studies. Even if a particular strategy or configuration was only explored in a single paper, it was still included to ensure the taxonomy reflects the full diversity of approaches currently under investigation. Following the initial extraction and organization of the data, early versions of the taxonomy were collaboratively discussed within the research team to validate its conceptual structure and identify areas for refinement. This iterative process led to the final version presented in Fig. 6.

It is important to emphasize that this taxonomy is not intended to be closed. Instead, it should serve as a foundation for the community to build upon, refine, and adapt as the field continues to grow and mature. By categorizing the reviewed works, the taxonomy facilitates a clearer understanding of how XR technologies can be tailored to enhance stroke rehabilitation outcomes. It also provides an organizational framework that makes it easier to identify where new strategies, features, or dimensions might be integrated in the future.

5.3. Directions for future work

Based on the review, we suggest the following directions for future research in the area of personalized XR for stroke rehabilitation, emphasizing the need to address existing gaps and expand understanding of this promising field:

- **Development of adaptive algorithms:** Future research should continue to focus on creating more sophisticated algorithms capable of real-time adjustments to XR environments based on the survivor's performance, physiological feedback, or cognitive state [20,32,48];
- **Integration of multimodal data:** Combining data from various sources, such as gaze tracking, gesture recognition, physiological sensors, or historical progress logs, can provide a holistic understanding of the survivor's state. Research should explore how to seamlessly integrate and process this data for more effective personalization [40,50,99];
- **Co-creation with stakeholders:** Involving stroke survivors, caregivers, and healthcare professionals in the design and development of XR solutions is critical. Future work should focus on participatory design methods to ensure the usability, accessibility, and relevance of these technologies in personalized solutions [12,47,49];
- **Social components:** Investigating how XR can incorporate social interactions, such as group therapy, may address the isolation often associated with rehabilitation, promoting engagement and motivation [16,100];
- **Evaluation in real-world contexts:** Research should prioritize testing personalized XR systems in real-world settings, such as rehabilitation centers or survivors' homes. This will help determine their practical applicability, reliability, and impact under diverse conditions [2,43];
- **Long-term effectiveness studies:** While many studies focus on short-term benefits, future work should assess the sustained impact of personalized XR interventions on recovery rates, functional improvements, and quality of life over extended periods [28,33];
- **Ethical and privacy considerations:** As XR systems collect large amounts of personal data, it is essential to investigate strategies for safeguarding user privacy and addressing ethical concerns related to data security, bias, and consent, among others [101];
- **Improve reporting**: understanding when XR is introduced along the rehabilitation timeline is paramount, as the suitability and effectiveness of XR may vary depending on the individual's physical and cognitive condition at each stage. Clear reporting of this and other similar aspects would not only enhance study comparison, but also support the development of stage-appropriate interventions.

5.4. Study limitations

While the work presented here provides valuable insights, it is essential to recognize the limitations of the analysis conducted. Scoping reviews are bound by methodological constraints, including the scope of the databases searched, the inclusion and exclusion criteria applied, and the temporal and thematic boundaries of the study. As a result, certain relevant studies may have been inadvertently excluded due to publication dates, database restrictions, or the narrow focus on specific research parameters. These factors could lead to an incomplete representation of the field and must be acknowledged when interpreting the findings. Incorporating snowballing in our methodology could have helped avoid missing relevant literature, although it may also introduce a level of subjectivity that might complicate reproducibility. Also, since this is a scoping review, we did not review the quality of the surveyed studies, since this is not a mandatory component of the methodology. As such, a bias in the data cannot be ruled out (e.g. over-representation of works from less experienced researchers).

The time interval for this review, spanning 2020 to 2024, was chosen to focus on recent advancements in XR technologies and their applications in stroke rehabilitation. This ensures the analysis captures the latest innovations and reflects current trends. However, this focus also excludes earlier foundational research that might provide a richer understanding of the historical progression and contextual grounding of personalized XR in rehabilitation. By omitting studies conducted prior to 2020, the review may overlook developments that have shaped the current state of the art, leaving gaps in understanding the evolution of key methodologies and technologies.

The number of publications analyzed, 39 out of 82 initially identified, demonstrates the rigor applied in selecting studies that align with the review's objectives. However, this relatively small sample size represents only a subset of the extensive research landscape. Some studies that did not meet the inclusion criteria but could still contribute meaningful insights were excluded. Expanding the review to consider a broader range of studies, including those with varied methodologies or contexts, could yield a more comprehensive and nuanced understanding of XR's role in stroke personalized rehabilitation.

Additionally, this review did not address several critical topics that warrant further exploration. For instance, ethical considerations related to personalized XR applications, issues of cost and accessibility that influence the scalability of these technologies, and the long-term sustainability of XR-based rehabilitation programs remain unexamined. These aspects are essential for ensuring that XR solutions are not only scientifically effective but also practical and scalable for diverse populations of stroke survivors. Future work must delve into these areas to create a holistic view for XR-based rehabilitation that addresses both clinical and societal needs.

6. Conclusions

Stroke significantly impacts millions of individuals worldwide, leading to physical impairments such as paralysis or difficulty in movement, speech challenges, and cognitive deficits like memory loss or difficulty concentrating. Beyond physical effects, strokes can cause emotional distress, anxiety, and depression, all of which can diminish the quality of life and require ongoing care and support.

Regardless, there is often a lack of personalization in rehabilitation activities, leading to standardized approaches that fail to address individual differences. Stroke survivors are all different, with varying levels of impairments, recovery needs, and personal goals. This lack of customization can result in frustration, loss of motivation, and diminished engagement, ultimately hindering the rehabilitation process and slowing recovery.

This work contributes to the field by presenting a scoping review of personalized XR in stroke rehabilitation, offering a comprehensive analysis of existing studies and solutions. The review aims to provide an understanding of the current landscape, identify research gaps, and offer a systematic perspective to guide future advancements in this area. To achieve this, we analyzed existing literature published between 2020 and 2024, focusing on studies indexed in the SCOPUS database. A total of 82 were initially identified. Each publication was carefully reviewed to determine its relevance to the topic, with 39 publications ultimately satisfying the defined inclusion criteria.

A high-level overview revealed key insights into the advancements and challenges in integrating personalized XR into stroke rehabilitation. This analysis highlights trends, areas of progress, and opportunities for future work to enhance personalized and effective rehabilitation solutions using XR technologies. The analysis emphasizes a strong focus on upper-limb physical rehabilitation is evident, while fewer works address lower-limb recovery or cognitive rehabilitation. Additionally, AR-based solutions or hybrid VR/AR approaches remain largely unexplored, potentially due to challenges in perceptual integration and user interaction. Regarding personalization strategies, behavioral tracking, and rule-based approaches are the most commonly used, demonstrating an emphasis on adapting XR environments based on users' movements and predefined rules. The predominant mode of personalization is automatic (near 46.2%), allowing real-time adjustments, with synchronous personalization appearing in 19 works (around 48.7%), reinforcing the importance of immediate feedback.

In terms of operational mode, most studies focused on individual rehabilitation, though there is potential for collaborative scenarios that could enhance motivation/engagement. Only 12 studies (close to 31%) incorporated a monitoring tool or visualization dashboard, suggesting limited attention to data tracking for long-term progress assessment. Additionally, regarding user evaluation, results indicate that nearly half of the works conducted direct tests with stroke survivors, either in rehabilitation centers or home settings. However, only 12% of the studies involved 2–5 rehabilitation sessions, while 42.4% lasted between 10–60 min, raising questions about the depth and consistency. Moreover, therapists played an active role in 12 studies (approximately 36.4%), contributing to various aspects, such as supervising sessions, selecting participants, adjusting parameters, guiding rehabilitation exercises, and participating in data analysis, thus emphasizing the relevance of clinical expertise in refining personalized XR-based rehabilitation solutions.

Overall, by offering a consolidated view of the field, we aim to support the creation of more effective, personalized, and engaging tools for stroke survivors and their caregivers, leading to better rehabilitation results and improved quality of life.

CRediT authorship contribution statement

Inês Figueiredo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bernardo Marques:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sérgio Oliveira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Bianca Guerreiro:** Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation, Conceptualization. **Samuel Silva:** Writing – original draft, Validation, Formal analysis, Data curation. **Paula Amorim:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Tiago Araújo:** Writing – original draft, Validation, Formal analysis, Data curation. **Liliana Vale Costa:** Writing – original draft, Validation, Formal analysis, Data curation. **Carlos Ferreira:** Writing – original draft, Validation, Formal analysis, Data curation. **Paulo Dias:** Writing – original draft, Formal analysis, Data curation. **Beatriz Sousa Santos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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