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Review

Augmented Reality in Upper Limb Function Recovery after Stroke: A Critical Synthesis and Clinical Implementation Perspectives

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Abstract: Restoring upper limb function continues to be a significant challenge for individuals recovering from stroke. Augmented reality (AR) has developed into a promising tool to improve the efficiency of neuromotor rehabilitation via methods like gamification, enhanced sensory feedback, and focused task-oriented practice. A thorough synthesis of the existing evidence is essential to inform clinical application and upcoming studies. This narrative review intends to integrate and critically assess current scientific findings regarding the effectiveness, underlying mechanisms, and practicality of applying AR-based interventions in upper limb rehabilitation post-stroke. A narrative and interpretive review of the literature was conducted, underpinned by a thematic analysis framework. To identify relevant literature, a strategic, though not exhaustive, search of primary databases (PubMed, Scopus, Web of Science) was performed, spanning the years 2013-2024. It is important to clarify that this is a narrative review, not a systematic review or meta-analysis; its purpose is to synthesize, critically interpret, and contextualize the existing evidence rather than to provide a quantitative summary of effect sizes. The research consistently shows that AR, employed alongside standard treatment, results in considerably larger enhancements in the FMA-UE score (with a reported adjusted mean difference ranging from 4 to 7 points, and a small-to-moderate effect size [Cohen's d between 0.3 and 0.6] in the subacute recovery phase) , particularly during the subacute recovery phase.. The efficacy is influenced by factors like the extent of the deficit, the structure of the tasks (which favor bimanual and ecological tasks) and the level of gamification. The effects on intricate functional metrics (ARAT) are more inconsistent. Patient acceptance is extremely high; however, obstacles to implementation like costs, time to set up, and the requirement for smooth integration into clinical workflows continue to pose significant challenges. Critical gaps involve the absence of cost-effectiveness analyses, technological diversity, and the requirement for participatory evaluations that prioritize quality of life. AR represents an effective and feasible adjunctive intervention for upper limb rehabilitation after stroke, acting as an amplifier of therapeutic principles based on neuroplasticity. To achieve its full potential, implementation must be strategic, patient-centered, and tailored to the clinical context. Future research should focus on pragmatic comparative efficacy studies, optimization of personalization, and robust cost-benefit analyses. This synthesis provides a framework for evidence-based use of AR and identifies priority directions for innovation and integration into health systems.

Keywords: stroke, neurological recovery, upper limb, augmented reality, movement therapy, neuroplasticity

1. Introduction

The multidimensional burden of stroke and the recovery paradigm

Stroke is the second leading cause of death and the primary cause of acquired adult disability worldwide. Its impact extends beyond the individual, profoundly affecting families and healthcare systems [1]. Among the after-effects of a stroke, upper limb motor impairment is notable as one of the most restrictive. About seventy-five percent of patients exhibit notable arm and hand dysfunction at the start, and for many, recovery after six months is less than ideal, with around 30-60% retaining some level of functional impairment [2,3]. This condition diminishes independence in fundamental (dressing, eating, personal care) and instrumental (cooking, managing finances) daily tasks, resulting in greater reliance on others, decreased self-worth, and an elevated risk of depression [4]. Consequently, regaining upper limb function is not merely a physiotherapy objective, but an essential condition for the survivor's restoration of personal identity and social inclusion.

The modern approach to post-stroke neurorehabilitation is grounded in robust neurobiological principles, namely activity-dependent neuroplasticity, which necessitates intensive, repetitive, and task-specific practice [5]. However, the translation of these principles into conventional (classical) therapy is fraught with practical barriers that limit its real-world effectiveness. Firstly, the resource-intensive nature of one-on-one therapy makes it difficult to achieve the high intensity and repetition required for optimal plasticity within strained healthcare systems. Secondly, the inherent monotony of repetitive exercises frequently leads to diminished patient motivation, boredom, and subsequent non-adherence, directly undermining the dose-response relationship essential for recovery [6]. Thirdly, and perhaps most critically, the clinical environment itself presents a "reality gap": it provides a simplified sensory and functional context that pales in comparison to the complexity and unpredictability of real-life situations. This limits the ecological validity of training and hinders the transfer of acquired motor skills to meaningful daily activities.

It is precisely at the intersection of these limitationsthe need for intensity, engagement, and ecological relevancet hat AR emerges not as a replacement for the therapist, but as a strategic and rational therapeutic amplifier. AR directly addresses the "reality gap" by overlaying interactive digital content onto the patient's physical environment, creating enriched, controllable, yet ecologically valid training scenarios [7]. To counter monotony and poor adherence, AR leverages gamification embedding exercises within engaging game narratives with points, levels, and rewards which taps into dopaminergic reward pathways to boost intrinsic motivation and prolong voluntary practice [8]. Furthermore, to compensate for the lack of intensive, error-driven learning, AR provides instantaneous, augmented visual and auditory feedback. This feedback can guide the motor cortex toward correct movement patterns, effectively bypassing proprioceptive deficits and enhancing motor learning [9]. Finally, by simulating Activities of Daily Living (ADL) such as "pouring" a virtual glass of water or "reaching" for virtual objects, AR facilitates a more direct transfer of clinic-based gains to home-based function, thereby addressing the core issue of ecological validity [10].

These constraints clearly emphasize the necessity for a significant advancement from an effective treatment in optimal circumstances to one that is impactful, appealing, attainable, and ecologically valid in routine applications. This is the point at which assistive technologies for recovery are utilized, not as replacements for the therapist, but as enhancers and elements that elevate the effectiveness of the intervention.

Augmented Reality: from technological concept to rational therapeutic tool

AR has progressed from mere technological interest to becoming a significant therapeutic tool in neurorehabilitation. The core idea, the contextual and real-time integration of digital content onto the physical environment, provides a distinctive training setting [7]. In contrast to immersive virtual reality, which may cause discomfort or disorientation, AR maintains the patient's connection to the immediate environment, aiding in a more seamless incorporation of the practiced skills.

The neurophysiological basis for employing AR is compelling. By employing gamification (turning exercises into games with scores and levels), AR activates dopaminergic systems linked to reward and learning, enhancing intrinsic motivation and extending the length of voluntary practice [8]. Instantaneous and accurate augmented visual feedback can offset proprioceptive deficits, steering the motor cortex and cerebellar-thalamo-cortical networks more efficiently toward appropriate movement patterns [9]. Moreover, AR facilitates the training of activities of daily living (ADL) within a realistic yet controlled setting (e.g., interacting with virtual objects placed on a real table), enhancing functional transfer [10].

Clinico-pathological Challenges and Knowledge Deficiencies

Although the potential is evident, incorporating AR into clinical workflows presents essential challenges and inquiries that demand thorough critical examination:

• The challenge of cost versus performance: Advanced AR systems come with high price tags. Is the impact significant enough to warrant the investment relative to standard treatment? [11]

• The challenge of personalization versus standardization: How can we reconcile the requirement for individualized protocols (customized according to the severity of the deficit) with the benefits of a standardized, scalable, and easily implementable protocol?

• Knowledge gaps: Which clinical patient phenotype (e.g., flaccid vs. spastic hemiparesis, acute vs. chronic phase) benefits most from AR? What is the ideal "dose" (how often, how long, complexity of tasks)? Which elements of AR (gamification, visual feedback, bimanual characteristics) are the most effective in therapy? [12]

• Methodological gaps: The current body of literature is disjointed, consisting of small pilot studies that vary in the technology employed, the populations targeted, and the outcomes reported. A synthesis is required to analyze these data, pinpoint consistent signals, and emphasize methodological gaps to inform strong future research [13].

Aim, objectives, and innovations of this review

The purpose of this critical review is to evaluate, synthesize and contextualize the current state of knowledge regarding the efficacy of augmented reality-assisted interventions for upper limb function recovery after stroke, providing a balanced perspective on the potential, limitations and future directions.The specific objectives are:
To address this central question, the specific objectives are:

To carry out a critical mapping of the specialized literature, highlighting the typologies of augmented recovery systems used and the characteristics of the populations studied.

To synthesize the evidence of efficacy at the motor (tone, coordination, control) and functional levels, based on standardized assessment tools (FMA-UE, ARAT, Box and Block Test).

To analyze in depth the moderating factors (recovery phase, technological characteristics, therapeutic dose) that seem to influence the outcome.

To identify and discuss major methodological gaps in existing studies and to formulate recommendations for improving the quality of research.

To develop clear practical implications for clinicians who wish to integrate augmented recovery into their practice and propose robust future research directions.

Expected practical implications

The results of this important review aim to directly influence clinical practice and research.

• It will serve as a resource for clinicians and rehabilitation center administrators to make well-informed choices about adopting AR, indicating for whom, when, and how this technology may offer the greatest advantages.

• It will pinpoint for researchers the most promising and essential research avenues, along with methodological traps to steer clear of in upcoming studies.

• In the end, by elucidating and enhancing the route to efficient AR integration, the assessment seeks to aid in bettering functional results and quality of life for stroke survivors, assisting them in recovering not just mobility, but also autonomy and optimism.

1. Materials and Methods

2.1. Review Design and Framework

This article is a narrative review with a critical and interpretative synthesis of the literature. In contrast to a systematic review, which aims for exhaustive coverage and quantitative meta-analysis, this review was designed to provide a contextualized, evaluative, and hypothesis-generating perspective on the use of Augmented Reality (AR) in post-stroke upper limb rehabilitation [14,15]. The methodology is reported with sufficient detail to ensure transparency and reproducibility, while acknowledging the inherent limitations of the narrative format.

2.2. Research Question (PICOS Framework)

This review was guided by the following pre-defined research question, structured according to the PICOS framework:

Population (P): Adults (≥18 years) with upper limb motor impairment following an ischemic or hemorrhagic stroke, in any phase of recovery (acute, subacute, chronic).

Intervention (I): Any therapeutic program incorporating Augmented Reality (AR) as a primary or adjunct component for upper limb motor training (including projector-based, tablet-based, and wearable systems such as Microsoft HoloLens).

Comparison (C): Conventional therapy (dose-matched or usual care), placebo/sham interventions, or no additional intervention. Single-arm feasibility studies were also considered for contextual data on acceptability and adherence.

Outcomes (O): Primary: Motor impairment (Fugl-Meyer Upper Extremity Assessment - FMA-UE), functional performance (Action Research Arm Test - ARAT), and manual dexterity (Box and Block Test). Secondary: Spasticity (Modified Ashworth

Scale), quality of life/independence (Motor Activity Log), and patient-reported acceptability/satisfaction.

Study Design (S): Priority was given to randomized controlled trials (RCTs) and controlled clinical trials (CCTs). To capture the full breadth of the field, feasibility studies, pilot studies, case series, and previous reviews/meta-analyses were also included for contextualization.

2.3. Search Strategy

A systematic, though not exhaustive, literature search was conducted in November 2024 across four major electronic databases: PubMed/MEDLINE, Scopus, Web of Science, and IEEE Xplore (to capture technical and engineering perspectives). The search covered the period from January 2013 to October 2024 to reflect the most recent technological and clinical advancements. The following search string was used, adapted as necessary for each database:

("stroke" OR "cerebrovascular accident" OR "post-stroke") AND ("augmented reality" OR "mixed reality" OR "AR therapy" OR "exergam*") AND ("upper limb" OR "upper extremity" OR "arm" OR "hand") AND ("rehabilitation" OR "recovery" OR "motor function" OR "neurorehabilitation")

2.4. Study Selection Process

The selection process was conducted in three stages by a single reviewer (RVB), with a consistency check on a 20% random sample by a second reviewer (AC) to minimize selection bias [16]:

Title and Abstract Screening: Titles and abstracts of all retrieved records were screened against the PICOS criteria. Records clearly irrelevant were excluded.

Full-Text Retrieval: Full texts of potentially relevant articles were obtained.

Full-Text Assessment: Full texts were evaluated against the inclusion criteria. Reasons for exclusion at this stage were documented.

2.5. Data Extraction

A standardized data extraction matrix was developed in Microsoft Excel. From each included study, the following information was extracted: author(s) and year, study design, sample size and participant characteristics (age, time post-stroke, baseline impairment severity), details of the AR intervention (technology type, tasks, duration, frequency), comparison group intervention, primary and secondary outcomes, main findings, and author-identified limitations.

2.6. Quality and Risk of Bias Assessment

Given the heterogeneity of included study designs, a single universal risk of bias tool was not applied. Instead, a tailored critical appraisal was conducted:

For randomized controlled trials, the Cochrane Risk of Bias 2 (RoB 2) tool was used to assess randomization, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting [17].

For non-randomized and feasibility studies, key quality indicators were assessed: clarity of intervention description, comparability of groups at baseline (where applicable), attrition rates, use of blinded outcome assessors, and intention-to-treat analysis.

The purpose of this appraisal was not to exclude studies, but to contextualize findings and grade the strength of evidence in the synthesis.

2.7. Data Synthesis and Analysis

Due to the narrative design and heterogeneity of interventions and outcomes, a meta-analysis was not appropriate. Instead, a thematic and interpretative synthesis was performed [18]. Extracted data were grouped and analyzed thematically according to the following pre-defined dimensions derived from the research question:

Clinical Effectiveness: Comparative effects of AR vs. control on FMA-UE, ARAT, and Box and Block Test.

Technological Mechanisms: Relationship between AR features (feedback type, gamification, task type) and reported outcomes.

Moderating Factors: Influence of patient characteristics (severity, chronicity) and intervention dose on effect size.

Feasibility and Implementation: Data on acceptability, satisfaction, cost, and practical barriers.**3. Results**

Following the outlined search strategy and selection criteria, a total of 45 pertinent publications were located and incorporated into this critical synthesis. This consisted of 18 randomized clinical trials (RCTs), 12 non-randomized controlled trials (CCTs) or feasibility studies, 8 pilot/case series studies, and 7 reviews/prospective articles released from 2014 to 2025. Table 1 summarizes the key features of the primary studies included. The thematic analysis revealed four primary outcome dimensions, which are presented below.

Table 1. General characteristics of the included primary studies (n=38).

Characteristic	Description / Range
Year of Publication	2014 – 2024 (majority between 2018-2023)
Sample Size (per study)	8 – 96 participants (median = 24)
Post-Stroke Phase	Acute (<1 month): 5 studies; Subacute (1-6 months): 22 studies; Chronic (>6 months): 11 studies
AR Technology Used	Screen/Projector (2D): 15 studies; Wearable Devices (e.g., Microsoft HoloLens, smartglasses): 12 studies; Marker-based systems with tablet/smartphone: 11 studies
Intervention Duration	3 – 12 weeks (most frequently 4-6 weeks)
Sessions per Week	3 – 5 sessions (most frequently 3 sessions)
Session Duration	20 – 60 minutes (most frequently 30-45 minutes)

Global Motor Function (Fugl-Meyer Assessment - FMA-UE)

Most moderate-to-high quality RCTs indicated larger enhancements in FMA-UE scores in the AR group relative to the standard therapy group. In a recent RCT (n=62) examining a projector-based AR approach versus standard physiotherapy during the subacute phase, the AR group demonstrated a notably larger average improvement (adjusted mean difference [AMD]: 5.8 points, 95% CI: 1.9–9.7, p=0.004) [19]. This pattern has been observed in additional research, especially among patients in the subacute phase, where the impacts seem to be more significant [20]. Nonetheless, a prior systematic review indicates that while the differences are statistically significant, the clinical effect size varies from small to moderate (Cohen's g between 0.3 and 0.6), implying that AR serves as an effective complement but not a groundbreaking substitute for traditional therapy [19-21].

Functional and Hand Function (ARAT, Box and Block Assessment)

In contrast to the relatively consistent improvements observed on the FMA-UE, outcomes on activity-based scales such as the Action Research Arm Test (ARAT) are markedly more heterogeneous. While some studies report significant gains for instance, a randomized controlled trial evaluating a wearable AR system for grip training noted notable enhancements specifically in the grip subscale of the ARAT compared to controls (p=0.02) [22] others have found no significant differences in total ARAT scores between AR and conventional therapy groups [23].

This inconsistency, however, is not random but rather illuminates a critical mechanistic insight derived from our thematic analysis: the transfer of motor gains to complex functional performance is not automatic; it is highly dependent on the ecological validity and task-specific design of the AR intervention. Our synthesis reveals a clear pattern: AR protocols that yielded significant ARAT improvements were those that moved beyond training isolated, decontextualized movements (e.g., flexion/extension in a virtual plane) and instead simulated complex, multi-step Activities of Daily Living (ADLs) (e.g., reaching for, grasping, and manipulating a virtual cup to "pour" water) [24]. When AR tasks closely mimic real-world functional demands, they appear to facilitate a more direct transfer of motor learning to the clinic-based functional assessments like the ARAT. Conversely, AR systems designed primarily as "repetition engines" for joint movements, while effective at reducing impairment (FMA-UE), may fail to engage the cognitive and motor planning networks required for integrated functional tasks, thus showing limited transfer on scales like the ARAT. This finding underscores that for AR to be functionally transformative, its design must prioritize task specificity and ecological validity, not just repetition and feedback.

Action Mechanisms and Technological Features of Modulation

Game-based Learning and Improved Feedback

A robust agreement appears in the literature highlighting the essential significance of gamification and enhanced visual feedback. Systems incorporating game elements (levels, scores, visual rewards) showed substantially greater adherence and patient satisfaction rates (p<0.05) than neutral AR systems or traditional therapy [25, 26]. Immediate visual feedback regarding movement path or precision seems to enhance quicker implicit learning and correction of errors, a process backed by research that has noted positive alterations in motor cortical connectivity [27].

Type of Task: Bimanual vs. Unimanual, Virtual vs. Simulated

The nature of the task also moderates effectiveness. Interventions utilizing bimanual tasks in AR, with the healthy limb engaging with the real world and the affected limb interacting with virtual items, have demonstrated encouraging outcomes in enhancing movement coordination and symmetry [28].

Clinical Aspects Influencing Reaction to Treatment

Initial Severity of Deficit: Patients exhibiting moderate deficits (initial FMA-UE score ranging from 20 to 40) seem to gain the most advantage from AR [29, 30]. Individuals with severe impairments (FMA-UE <20) might need substantial interface modifications, and benefits could be less pronounced at the motor level but noteworthy for motivation. Individuals with minor impairments might achieve a “ceiling” rapidly with conventional treatment [21].

Recovery Phase: The most reliable proof of effectiveness is found in the subacute phase (1–6 months), an essential timeframe for neuroplasticity [19, 20]. During the chronic phase (>6 months), AR may offer considerable advantages, but these are generally more related to functional enhancement and quality of life rather than gross motor recovery [31].

Dose-Response: An analysis of various studies shows a favorable connection between "dose" (overall hours of AR training) and effect size. Programs totaling fewer than 15 hours of training (for example, 3 weeks with 3 sessions per week of 30 minutes each) usually exhibit minimal clinical effects [32].

Viability, Suitability, and Obstacles to Execution

The feasibility aspects are mainly reported in a positive light. Patient acceptability is notably high (>85% in many studies), with patients characterizing the intervention as "engaging," "enjoyable," and "giving a sense of achievement" [33]. Therapists view AR as a beneficial tool for sustaining motivation and standardizing aspects of training; however, they also identify obstacles: the upfront expense of the equipment, the time needed for setup and system familiarization, and the challenge of smoothly incorporating AR scenarios into intricate personalized therapeutic objectives [34]. Analyses of cost-effectiveness are still quite uncommon in this domain, as shown in Table 2.

Table 2. Summary of Evidence on Augmented Reality (AR) for Upper Limb Rehabilitation After Stroke

Domain	Findings	Level of Evidence	Clinical Interpretation
Motor Impairment (FMA-UE)	AR combined with conventional therapy produces significantly greater improvements in upper limb motor impairment compared with conventional therapy alone, especially in the subacute phase. Mean differences typically range between 4–7 FMA-UE points.	Moderate–High (multiple RCTs, systematic reviews)	AR is an effective *adjunct* to enhance motor recovery, particularly when neuroplasticity is maximal (1–6 months post-stroke).
Hand Dexterity (Box and Block Test)	Consistent moderate improvements observed across chronic and subacute stroke populations when AR is used for task-oriented practice.	Moderate	AR improves fine motor control and speed of grasp-release movements.
Functional Performance (ARAT)	Mixed results. Improvements are more likely when AR tasks are ecologically valid (real-object interaction, bimanual tasks).	Low–Moderate	AR improves functional use only when designed to mimic real-world activities.
Neuroplasticity & Motor Learning	AR-based training enhances cortical excitability and promotes motor reorganization through enriched feedback, repetition, and error-based learning.	Moderate (neurophysiological studies)	AR acts as a *neuroplasticity amplifier* rather than an independent therapy.
Motivation and Adherence	Gamified AR leads to significantly higher engagement, longer practice times, and higher patient satisfaction (>85% positive ratings).	High	AR addresses a key limitation of conventional therapy: low adherence and boredom.
Phase of Stroke	Largest benefits observed in the subacute phase; chronic patients show smaller but still meaningful functional and quality-of-life gains.	High	AR should be prioritized early but remains useful in chronic rehabilitation.
Severity of Deficit	Patients with moderate baseline impairment benefit most; severe patients require simplified interfaces; mild cases show ceiling effects.	Moderate	Patient selection is critical for maximizing benefit.
Dose-Response Relationship	Meaningful clinical effects require ≥15–20 hours of AR training. Shorter programs yield limited benefit.	Moderate	AR should be prescribed with adequate intensity, similar to conventional therapy.
Feasibility	High patient acceptance and therapist-rated usefulness; main barriers are cost, setup time, and integration into workflow.	Moderate	AR is feasible but requires organizational adaptation.
Cost-Effectiveness	Insufficient evidence; few studies evaluate long-term economic impact.	Low	Economic justification remains a major research gap.

2. Discussion

This narrative review aimed to synthesize and critically assess the current evidence regarding the effectiveness, mechanisms, and practicality of utilizing AR for restoring upper limb motor function following a stroke. The analysis provided verifies that AR is a hopeful supplementary therapeutic approach that can enhance motivation and result in notable advancements, particularly in overall motor function and dexterity. Nonetheless, the findings emphasize a multifaceted reality, in which success is influenced by various technological, clinical, and situational factors [35, 36] .

Incorporation and Analysis of Key Finding

Consistent with the original hypothesis, most RCTs of high methodological quality show that when AR is combined with standard therapy, it leads to greater enhancements in the FMA-UE score compared to standard therapy by itself [19, 20]. This indicates that the processes of AR (augmented feedback, gamification, intense repetition) meaningfully align with the core principles of neuroplasticity [28]. Nevertheless, the small effect size noted in earlier reviews [21] acts as a significant clinical warning: AR is not a cure-all, but rather a therapy enhancer. The greater difference noted in the ARAT scale [22, 23] emphasizes a key challenge: converting motor advancements into intricate functional abilities probably necessitates that AR tasks be crafted with enhanced ecological and functional significance [24].

An important finding is that the greatest advantage seems to happen during the subacute phase of stroke [20, 31]. This aligns well with the crucial period of neuroplasticity, indicating that AR might be effectively utilized as a timely catalyst for recovery. During the chronic phase, its role may transition to focusing on sustaining engagement, enhancing quality of life, and providing compensatory training [31, 33].

Mechanisms of Action and Implications for Intervention Design

This review highlights that the effectiveness of AR is deeply tied to how it is implemented. Gamification and enhanced feedback are not mere embellishments, but active factors that increase intrinsic motivation and can lead to longer and more attentive practice [26, 27]. In addition, the use of bimanual tasks and interfaces that combine real objects with virtual elementsseem to be a promising direction to facilitate transfer into daily activities. These findings provide a practical guide for clinicians and developers: AR intervention design should prioritize these active principles to maximize therapeutic impact [28, 29].

Limitations of the Review

This review has several limitations that must be acknowledged when interpreting its findings. First, in line with its narrative design, the literature search and study selection process, while strategic, was not exhaustive. A particularly noteworthy methodological limitation is that the screening and selection of studies were performed by a single reviewer. Although a consistency check was conducted on a random 20% sample to mitigate the risk of oversights, this approach is inherently susceptible to selection bias and may have inadvertently excluded relevant studies or overemphasized others based on the reviewer's subjective judgment [16]. Future systematic reviews on this topic should employ at least two independent reviewers to enhance reliability and reproducibility.

Second, the narrative and qualitative synthesis, while allowing for an in-depth thematic interpretation, does not permit precise quantitative conclusions regarding the pooled effect size of AR interventions. A meta-analysis would be required to provide such estimates, which was beyond the scope of this review.

Third, the included primary studies exhibited considerable heterogeneity in terms of AR technologies used, intervention protocols (duration, frequency, task types), patient populations (stroke phase, severity), and outcome measures. This diversity, while reflective of a nascent field, complicates direct comparisons and the formulation of standardized clinical recommendations. Finally, by including only English-language publications, we may have introduced a language bias, potentially omitting relevant studies published in other languages.*Future Research*

To advance the field from proof-of-concept to evidence-based clinical practice, future research must be prioritized and designed with greater methodological rigor and practical relevance. We propose the following three-tiered research agenda, ordered by urgency and impact:
Priority 1: Pragmatic Comparative Effectiveness Trials
The most pressing need is to move beyond efficacy studies under ideal conditions toward pragmatic randomized controlled trials that directly inform clinical decision-making. These trials should:
Compare AR-enhanced therapy head-to-head with dose-matched conventional therapy (not treatment as usual) to isolate the specific contribution of AR.

Evaluate scalable, off-the-shelf AR systems that could be readily implemented in real-world clinical settings, rather than expensive, research-grade prototypes.

Include health economic outcomes (cost per quality-adjusted life year [QALY], therapist time utilization) to build the business case for AR adoption [34].
Employ blinded assessors and intention-to-treat analysis to minimize bias [17].
Priority 2: Precision Rehabilitation and Adaptive Algorithms
To move from a one-size-fits-all approach to personalized medicine, research must identify predictors of treatment response and develop adaptive interventions. Specific research questions include:
Which clinical phenotypes (defined by lesion location, baseline impairment severity [FMA-UE strata], cognitive status, or proprioceptive integrity) derive the greatest benefit from AR? [29,30].
Can machine learning algorithms be developed to adjust task difficulty in real-time based on patient performance, maintaining the patient in an optimal "challenge point" zone for motor learning?
What is the optimal "dose" (session frequency, duration, total hours) of AR training for different recovery phases and severity levels? Dose-finding studies using factorial designs are urgently needed [32].
Priority 3: Implementation Science and Human Factors Research
Even the most effective intervention will fail if it cannot be integrated into clinical workflows. Future research should:
Employ mixed-methods designs (quantitative surveys combined with qualitative interviews) to systematically identify barriers and facilitators to AR adoption from the perspectives of patients, therapists, and administrators [34].
Develop and test theory-informed implementation strategies (e.g., therapist training programs, technical support bundles, workflow integration tools) to promote uptake and sustained use.
Evaluate the usability and acceptability of different AR form factors (projector-based vs. wearable headsets) in real-world clinical environments.

3. Conclusions

This essential literature review clearly shows that AR has proven to be a practical and promising supplementary therapeutic approach for the rehabilitation of upper limb function following a stroke. The evidence of effectiveness, while not revolutionary, is consistent: when incorporated into standard rehabilitation programs, AR can produce greater enhancements in overall motor function (measured by FMA-UE) and manual dexterity, particularly during the subacute stage of stroke, when neuroplasticity mechanisms are at their peak. Its beneficial effect is facilitated by solid therapeutic principles: boosting motivation via gamification, offering enhanced sensory feedback, and supporting task-focused repetitive practice.

The review emphasizes that technological potential does not inherently lead to overall clinical excellence. The success of AR depends on various elements: patient traits (degree and stage of the deficit), design of the intervention (task relevance, bimanual aspects, feedback quality), and the clinical environment in which it is used. Converting motor enhancements into significant functional benefits in everyday life continues to be a challenge and a key focus for future system advancements.

Based on the synthesized evidence, we propose the following specific, actionable recommendations for clinicians and rehabilitation services considering the integration of AR:

Patient Selection (WHO):

Priority candidates: Patients in the subacute phase (1-6 months post-stroke) with moderate upper limb impairment (baseline FMA-UE score between 20-40) appear to derive the greatest and most consistent benefit [19,20,29].

Consider with adaptations: Patients with severe impairment (FMA-UE < 20) may benefit from AR primarily for motivational purposes, but require simplified interfaces and therapist assistance. Patients with mild impairment may reach a ceiling effect quickly; AR can still be useful for maintaining engagement during late-stage rehabilitation [21].

Less suitable: Patients with severe cognitive impairment, neglect, or uncontrolled epilepsy may not be appropriate candidates without careful screening and adaptation.

Intervention Design (WHAT & HOW):

Prioritize ecological validity: Select AR systems and tasks that simulate Activities of Daily Living (ADL) (e.g., reaching for virtual objects on a real table, bimanual tasks like "pouring" or "stirring") rather than those that only train isolated joint movements. This is critical for functional transfer to scales like the ARAT [24,28].

Leverage gamification: Choose AR applications with embedded game elements (points, levels, rewards, narratives) to enhance motivation and adherence. The "fun factor" is not a luxury; it is a therapeutic mechanism that drives prolonged practice [8,25,26].

Ensure feedback richness: Prioritize systems that provide immediate, augmented visual or auditory feedback on movement accuracy and quality, as this appears to enhance motor learning, particularly in patients with proprioceptive deficits [9,27].

Dosing and Integration (WHEN & HOW MUCH):

Prescribe adequate intensity: Plan for a minimum of 15-20 hours of AR training over the intervention period to achieve clinically meaningful effects. Shorter programs (<15 hours) are unlikely to yield significant gains [32].

Integrate, do not replace: AR should be used as an adjunct to, not a substitute for, skilled therapist intervention. A typical model might involve 30-45 minutes of

AR training within a 60-minute therapy session, allowing the therapist to focus on hands-on techniques, patient education, and progression monitoring.

Plan for workflow integration: Anticipate an initial learning curve and setup time. Services should allocate resources for therapist training, technical support, and seamless scheduling to avoid disruption to clinical workflows [34].

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, R.V.B. and D.I.C.; methodology, A.C.; software, R.C.; validation, S.A.S.M. and V.C.; formal analysis, T.G.S.; investigation, A.C.; resources, V.C.; data curation, R.V.B.; writing—original draft preparation, R.B.V.; writing—review and editing, R.C.; visualization, A.C.; supervision, S.A.S.M.; project administration, A.C.; funding acquisition, R.V.B. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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